Towards Sustainability:

Direction for Life Cycle Assessment

by

Derek G. Selmes BEng., MSc

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Abstract

This thesis proposes that the state of sustainability – ensuring the welfare of global societies now and tomorrow – is a desirable objective that provides a robust goal for environmental management tools including LCA. Sustainability demands that the fundamental environmental issue – loss of natural capital – is actively addressed, including tackling critical, yet intangible resources such as biodiversity or processes such as assimilative capacity. The goal of sustainability, as interpreted in this thesis, is operationalised for business as a goal of *sustainable systems*.

The suitability and effectiveness of LCA methodology in promoting *sustainable systems* is examined. Through its life cycle perspective, LCA methodology is suitable to this objective – although its complexity puts off potential users. LCA does not have a pre-defined goal, thus its effectiveness in promoting sustainability will hinge upon the robustness of the goal employed. Unfortunately, definitions of sustainability employed within the LCA field are often weak. Furthermore, improvement assessment is no longer seen as a mandatory element of LCA. A strategic improvement assessment is however fundamental to the delivery of sustainable systems.

The thesis concludes that current LCA methodology could be applied towards the goal of sustainability but care must be taken in goal definition and the selection of appropriate impact criteria to maximise its effectiveness to this end. Best practice would include explicit use of an improvement assessment based on conceptual strategy. To this end, this thesis develops and presents an approach called *Life Cycle Assessment Towards Sustainability* (LCATS). The approach pre-defines the goal of *sustainable systems* and uses conceptual impact assessment and strategic improvement strategy designed to maximise the availability of natural capital.

In conclusion, LCATS presents a valuable LCA-based approach for promoting sustainable systems. With relatively straightforward methodology, LCATS can assist business in understanding how to be more sustainable; where and how they can exert company influence to positive environmental and economic advantage; and how to tackle unsustainable infrastructure during the transition to a sustainable system.

To Mum, Dad and Jen

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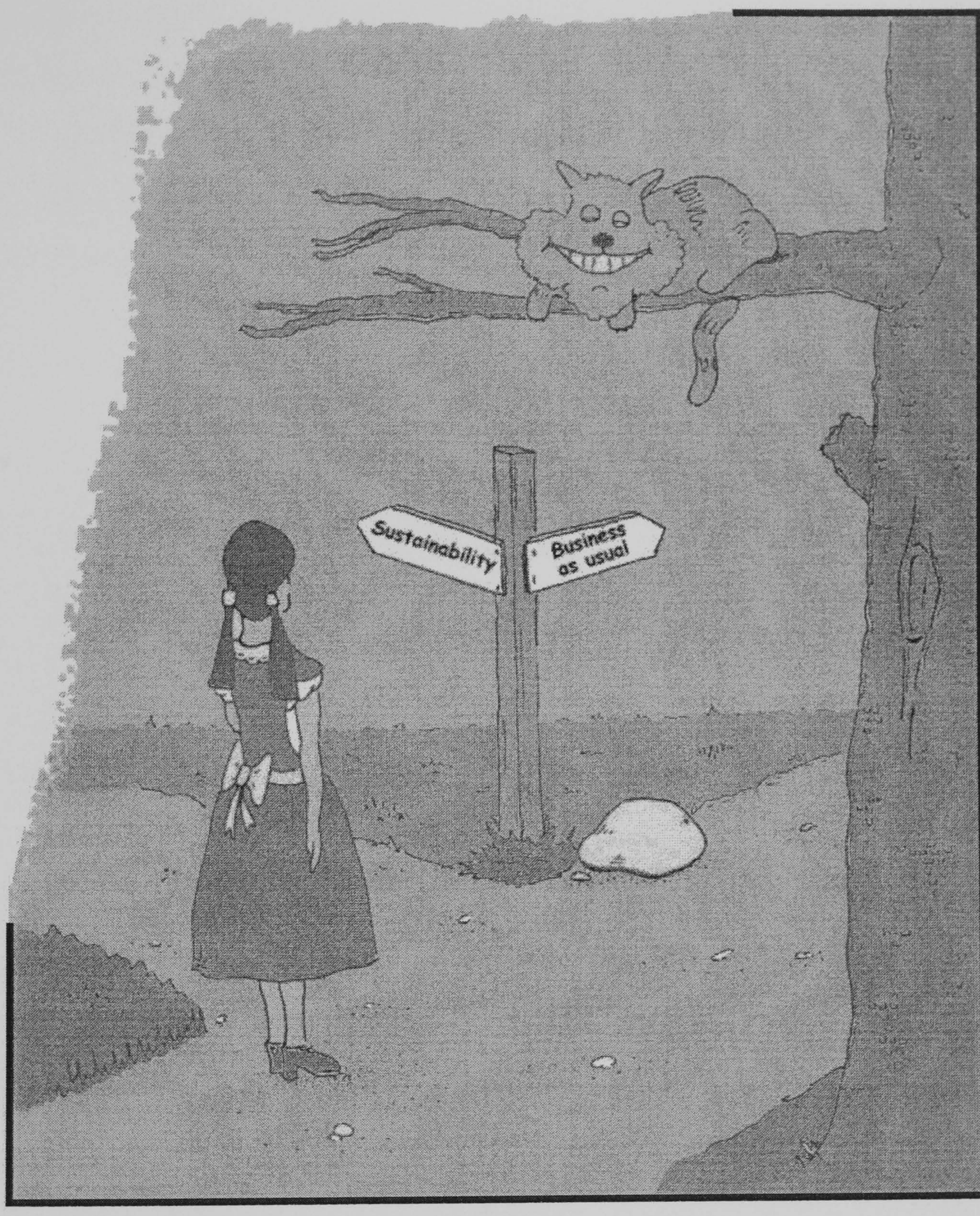
Glossary of Abbreviated Terms

DfE	Design for the Environment
EEA	European Environment Agency
EIA	Environmental Impact Assessment
IE	Industrial Ecology
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCATS	Life Cycle Assessment towards Sustainability
LP	Linear Programming
MIPS	Material Input Per unit of Service
SIA	Social Impact Assessment
TNS	The Natural Step
UNEP	United Nations Environment Programme
WCED	World Commission on Environment and Development



"Would you tell me, please, which way I ought to go from here?"
"That depends a good deal where you want to get to" said the cat.
"I don't much care where" said Alice.
"Then it doesn't much matter which way you go" said the cat.

Lewis Carol, Alice's Adventures in Wonderland, 1865

Introduction

Chapter 1 - Introduction

1.1 What is Life Cycle Assessment?

Life Cycle Assessment (LCA) is one of various environmental management tools currently available for mitigating environmental concerns [1]. Employed to its full, LCA examines environmental inputs and outputs related to a product or service life cycle from 'cradle-to-grave', i.e. from raw material extraction, through manufacture, reprocessing (where appropriate) to final disposal.

LCA is defined in ISO 14040 as [2]:

> "a technique for assessing the environmental aspects and potential impacts associated with a product, by:
>
> - compiling an inventory of relevant inputs and outputs of a product system;
> - evaluating the potential environmental impacts associated with those inputs and outputs;
> - interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study."

LCA is often employed as an analytical decision support tool [3,4]. Historically, it has found popular use comparing established ways of making and processing materials, for example comparing recycling with incineration as a waste management option [5]. Improvement is not seen as part of the LCA process – rather an application of it; nevertheless LCA is increasingly being seen as a tool for the delivery of more eco-efficient life cycles.

A more detailed introduction to life cycle assessment, including historical overview is provided in chapter 5.

1.2 Why use Life Cycle Assessment?

LCA is commonly used by industry, governments and other organisations [6] as it can go further than other environmental management tools in helping understanding and improving human interactions with the natural and social environment. It has the advantage of holistically assessing processes or activities within the context of a given life cycle, and does so in a manner that potential environmental impacts may be evaluated in the wider cradle-to-grave context and risks of 'problem shifting' may be minimised [7].

While LCA methodology continues to be developed, it has great potential – where appropriately deployed – to help forge a more sustainable future. This thesis investigates and expands on the salient features of LCA and develops strategies to maximise the potential of LCA as a tool for the practical achievement of sustainability.

1.3 Justification for the research

LCA methods continue to be developed and certain methodological elements (and their application) are still being debated intensively in the literature – see for example the International Journal of Life Cycle Assessment [8]. The issues in this thesis are of fundamental significance to LCA for the following reasons:

- Much LCA research either looks at one aspect of methodology or at one particular application of LCA, yet the ultimate intent of LCA as an environmental management tool has not been questioned. This thesis does so – particularly with respect to its use in promoting sustainability.
- There is a need for both maximal return on investment in LCA studies in terms of knowledge gained and efficiency in effort and cost effectiveness in general. The combination of environmental issues, stakeholder pressures and the need to keep costs to a minimum make it critical to gain maximum return on manpower and other resources invested in LCA studies. Such studies are often resource intensive, and therefore a burden on businesses – particularly SMEs – who are already under great pressure for time, money and human resources.

1.4 Research Question

Reducing environmental impact or tackling sustainability is increasingly becoming a prerequisite for being in business – in terms of litigation or stakeholder pressure for example – and yet there is still the requirement to keep costs (including management overhead) to a minimum. This results in a dilemma where business feels forced to trade-off the costs of environmental protection with the need for profit (see page 25). Appropriate and effective environmental management tools must therefore be available in order to effectively manage – and thus take responsibility for – our interactions with the natural environment.

LCA is becoming a key environmental management tool. In saying this, it does not necessarily follow that it results in significant gain with respect to environmental issues or sustainability. To examine LCA, its development and methodologies, with a view to assessing and maximising its potential use in the achievement of sustainability in practice, the following research question was therefore posed:

> **How should LCA methodology be configured such that it better promotes environmentally sound product systems, and thereby sustainability?**

Answering this question clearly requires both a good understanding of the ways in which product systems (i.e. products and supporting life cycle processes) affect the natural environment, sustainability and the LCA methodology itself.

Early in the work, it became apparent that despite considerable effort toward consensus on LCA approaches and guidelines – including standardisation by ISO – the field was awash with material ranging from the useful and informative, to the vague and conflicting, to the extremely complex. It was clear that LCA would be difficult for many to pick up and apply – especially novices or SMEs – if indeed it was considered for more than a moment in the first place. Indeed such criticism was found to be present in the literature. Contemplating these issues started the process that would ultimately shape the course of this work (see Figure 1 below).

In his book *in Earth's Company*, Frankel quotes Taiichi Ohno's useful approach to tackling problems [9]:

> "Underneath the 'cause' of a problem, the real cause is hidden. In every case, we must dig up the real cause be asking *why, why, why, why, why*."

This is essentially the approach that was employed here. As Frankel suggests, each question takes the analyst further and further away from the apparent problem at hand to increasingly abstract and philosophical questions. Given the confusion that arose during the initial reviews of LCA methodology, the first abstraction was to ask *why use Life Cycle Assessment at all?* The questioning that followed is summed up here:

Q. *Why do we use Life Cycle Assessment?*
A. In general, to approach sustainability by improving the environmental performance of product life cycles, or knowledge thereof.

Q. *Why be concerned about the environment?*
A. The availability of environmental goods and services directly impinge on business viability, quality of life, and indeed life itself.

Q. *Should we be sufficiently concerned with management of the environment to pursue environmentally sound product systems and sustainability?*
A. Yes. There is evidence that the behaviour of mankind is having an adverse and sometimes irreversible affect on the availability of environmental goods and services.

This line of enquiry led ultimately to existential questions such as *why be concerned with quality of life and life itself?* At this point, it was assumed that there was plenty of consensus that life and quality of life are **not** of questionable value. Working back from this assumption it was clear that, in order to answer the main research question, more time would have to be spent understanding the need for environmental management and the need to tackle sustainability *per se*. Only then would it be possible to assess the effectiveness of LCA methodology and therefore identify opportunities to improve configuration of the tool.

Figure 1 - Approach to the Research Question

In order to answer the main research question, it would be necessary to answer two sub-questions:

a) **What are fundamental issues that determine the need for environmental management tools including LCA?**

b) **How effective is current LCA methodology in promoting sustainable product systems?**

Accordingly, three steps are taken to answer the main research question – these are reflected in the three parts of the thesis. The objective of Part I is to answer sub-question (a) in understanding the nature of the impacts of mankind on the natural and social environment. The objective of Part II is to answer sub-question (b) by reviewing current LCA methodology with respect to knowledge gained in Part I. The objective of Part III is to build on knowledge gained on the effectiveness of LCA and to seek to examine ways in which LCA methodology could be configured or modified to make it usable in the quest for sustainability. This includes the testing of ideas using case studies.

1.5 Research Methodology

Most of the research presented in this thesis has employed qualitative methodology. This approach has been taken to pursue fundamental understanding and achieve the level of scope necessary to answer the research question. Reasoned arguments backed up with appropriate evidence have been employed to maintain objectivity as far as is possible. A description of the methods used in each of the three parts of the thesis now follows.

1.5.1 Methods Employed in Part I

The initial stage in researching and articulating current understanding of environmental issues involved a review of relevant information within published literature. Chapter 2 explores the nature of contemporary environmental concern. 'Milestones' in environmental issues are interpreted and discussed, identifying evidence supporting these concerns. Barriers and constraints to progress are also discussed before reaching some initial conclusions with respect to sub research question (a).

Chapter 3 of the thesis further answers sub research question (a) by developing a qualified definition of sustainability. The chapter employs critical review and comparison of key concepts to provide a basis for this definition. Limits to the use of natural capital are explored, interpreted and discussed. Through a process of reasoned argument a qualified definition of sustainability is then built up.

Chapter 4 of the thesis complements and consolidates the knowledge gained in chapters 2 and 3 through an evaluation of fundamentally unsustainable activities, reaching final conclusions with respect to sub research question (a). Evidence from the literature is reviewed and discussed. Key features of modern society are assessed for characteristics that contribute to current unsustainable behaviour. The findings are interpreted and the role of environmental management in promoting sustainability is discussed. An operational goal of a sustainable system is defined.

1.5.2 Methods Employed in Part II

In part II, the qualified definition of sustainability developed in part I – made operational as the goal of a sustainable system - is used as the framework with which to review LCA methodology and thereby answer sub-question (b).

Chapter 5 introduces life cycle assessment within a historical background and sets out the developing methodological features.

Chapter 6 forms a critique of accepted LCA methodology and examines its potential use towards the goal of sustainable systems. The interrelationship of the parts and various features of LCA is also investigated.

Chapter 7 considers LCA deployment as a whole. It examines the relationship between the supply of, and demand for, LCA methodology; makes comparison of different interpretations of sustainability employed; and assesses degree to which the approach fulfils the needs of sustainability as developed in part I. Chapter 7 closes with proposed features for an LCA approach to complement classic LCA in the pursuit of sustainable systems and draws final conclusions with respect to sub-question (b).

1.5.3 Methods employed in Part III

Part III builds on the findings of parts I and II and seeks to answer the main research question.

Chapter 8 develops and presents an LCA approach tailored for the purpose of achieving sustainable systems (as defined in part I).

Chapter 9 applies the LCA approach developed in chapter 8 to a published LCA case study. This is achieved through an examination of differences between the two approaches taken and the results found.

Part I - Environmental Crisis and the Challenge of Sustainability

“We should all be concerned about the future because we will have to spend the rest of our lives there.”

Charles Franklin Kettering, *Seed for Thought*, 1949.

“The crucial missing factor in all the bad news is the good news: there are options to these problems – and there are solutions.”

Medard Gabel, What the World Wants Project, 1997.

Chapter 2 - The Nature of the Environmental Crisis

2. Objectives

This chapter answers sub research question (a) through a critical review of relevant information within the published literature. The question was:

> **What are the fundamental issues that determine the need for environmental management tools including life cycle assessment?**

2.1 Introduction

It is often suggested in the media and elsewhere that there is a growing environmental and social crisis. The purpose of this chapter is to explore, interpret and discuss historical and contemporary environmental concern. The degree to which such concerns are valid is assessed. Barriers and constraints to progress are also discussed before reaching conclusions with respect to sub research question (a).

2.2 'Landmarks' of Concern for the Natural Environment

Records of environmental degradation caused by human activity have existed ever since mankind learned to write. Ponting discusses Sumerian records of approximately 3000BC where salination caused by irrigation precluded wheat production [10]. However, much contemporary environmental awareness stems from the 1960s and early 1970s. A brief list of landmarks of contemporary concern for the environment now follows.

2.2.1 Silent Spring

The publication of Rachel Carson's *Silent Spring* in 1962 is considered to have been a key influence to the beginnings of the environmental movement [11]. This book brought the dangers of chemical pesticides to public attention and challenged the practices being developed by agricultural scientists and being endorsed by governments. The use of the pesticide DDT was subsequently banned in industrialised countries [12].

2.2.2 The Club of Rome

The Club of Rome commissioned global modelling studies at the Massachusetts Institute of Technology (MIT) as part of its *Project on the Predicament of Mankind* [13]. This group of studies in the early 1970s culminated in the Club of Rome's publication of *The Limits to Growth.* [14] Changes in population, agricultural production, natural resource use, industrial production and pollution were included in the model as it was considered that these five factors [15]:

> "determine, and therefore ultimately limit, growth on this planet."

The conclusions of *The Limits to Growth* are reproduced in Figure 2 below. While the Meadows *et al* warning of 'sudden and uncontrollable decline in both population and industrial capacity' has not been realised in the thirty years since publication of *The Limits to Growth*, their prediction was that we would cross the limits to growth within one hundred years. As will be seen later, there is evidence that we are failing to adopt the more sustainable path proposed by Meadows *et al* in the conclusion of the book.

1. If the present growth trends in world population, industrialisation, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity.

2. It is possible to alter these growth trends and to establish a condition of ecological and economic sustainability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has equal opportunity to realise his individual human potential.

3. If the world's people decide to strive for this second outcome rather than the first, the sooner they begin working to attain it, the greater will be their chances of success.

from Meadows *et al*, 1972 [16].

Figure 2 - Conclusions of '*The Limits To Growth*'

2.2.3 UN Conference on the Human Environment

The UN conference on the Human Environment was held in Stockholm 1972. This was a milestone in articulating the rising awareness of the environmental problems of the modern age [17]. It provided a declaration on the human environment, an international action plan, a permanent environmental secretariat and an environmental fund [18].

2.2.4 The World Commission on Environment and Development

The World Commission on Environment and Development (WCED) was set up in 1984 by the United Nations General Assembly with the task of formulating a 'global agenda for change'. The UN themselves concede that in the 25 years following the Stockholm conference (discussed above) [19]:

> "only limited results were achieved in making the environment part of national development plans and decision-making,"

and that by this time:

> "environmental preservation was clearly becoming a matter of survival for everyone".

The WCED findings *Our Common Future* was published in 1987 [20] and is often referred to as *The Brundtland Report* (named after the WCED chairwoman Gro Harlem Brundtland). The report popularised the term 'sustainable development' as defined in Figure 3.

"Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

WCED, 1987 [21]

Figure 3 - Brundtland Definition

At the close of their final meeting, the WCED stated that [22]:

> "We remain convinced that it is possible to build a future that is prosperous, just, and secure... [the] possibility depends on all countries adopting the objective of sustainable development as the overriding goal and test of national policy and international co-operation. Such development can be defined as an approach to progress which meets the needs of the present without compromising the ability of future generations to meet their own needs. A successful transition to a sustainable development through the year 2000 and beyond requires a massive shift in societal objectives. It also requires the concerted and vigorous pursuit of a number of strategic imperatives."

The 'strategic imperatives' to which the WCED refer are the 8 principles of the Tokyo Declaration, published in *Our Common Future.* The first four principles of the declaration are the most significant and are discussed below.

2.2.4.1 The Tokyo Declaration

The first principle of the Tokyo Declaration [23] recommends stimulation of economic growth, particularly in the 'developing countries' in order to eliminate poverty. (Poverty was recognised by the World Commission as a major cause of environmental degradation.)

While there is a need to reduce the poverty suffered by many of the developing countries, it seems unwise of the Commission to have cast this first principle in terms of economic growth because normal economic growth is largely derived from unsustainable processes which contribute to poverty. The western expansionist economic model is known to be detrimentally exploitative of the planet's resources, which therefore undermines the Commission's own definition of sustainable development. Efforts to export the western economic model to developing countries contradict efforts to reduce environmental degradation [24]. It would have been better to couch this principle in terms of development rather than 'economic growth'. Indeed, from the perspective of sustainability, it would have been more appropriate to put the third principle – which addresses the environment – at the top of the declaration.

The second principle of the Tokyo Declaration goes some way to balance the call for economic growth by calling for a change in the quality of growth, including [25]:

> "better income distribution, reduced vulnerability to natural disasters and technological risks, improved health, [and] preservation of cultural heritage." This appears to qualify the first principle by demanding a "new kind [of growth] in which sustainability, equity, social justice, and security are firmly embedded as major social goals."

The third and most fundamental principle in the declaration – from the perspective of attaining sustainability – directly addressed environmental issues. It specifically recommends the conservation of environmental resources including "clean air, water, forests, and soils" and "maintaining genetic diversity". This principle also promotes efficient resource use, technological development and pollution prevention. Three key areas are thus addressed: resource conservation, biodiversity and assimilative capacity (see Figure 13 - Assimilative Capacity on page 46).

The fourth principle addresses population policies and advises incorporation of [26]:

> "education, health care, and the expansion of the livelihood base of the poor."

There was no mention of other issues such as population dislocation, loss of indigenous knowledge and self-sufficiency [27].

2.2.4.2 Successes and Failures of the World Commission on Environment and Development

While the work of the WCED was instrumental in increasing environmental awareness and putting sustainability on the political agenda, there are some serious shortcomings in the work. As explained later, there is a consensus that the expansionist economic model of the developed world plays a key role in environmental degradation. However, by recommending economic growth in the first principle of the Tokyo Declaration, the WCED appear to have promoted economic growth as the key way forward in terms of sustainability. Indefinite growth implies an exponential relationship which is impossible in a finite system. A second key criticism of the WCED is that at no point does the Tokyo Declaration mention the need for reduced material consumption, whereas the issue of resource consumption was subsequently identified by the UN as [28]:

> "the major cause of the continued deterioration of the global environment".

2.2.5 UN Conference on Environment and Development

Following the publication of the Brundtland Report, The UN General Assembly convened the United Nations Conference on Environment and Development (UNCED). The conference was held in Rio de Janeiro, Brazil 1992 and is known as the 'Earth Summit'. The purpose of the meeting was to review progress since previous conferences, including the 1972 Stockholm conference. The main aim was "to find an equitable balance between the economic, social and environmental needs of present and future generations" [29]. Further aims were to "lay the foundation for a global partnership between developed and developing countries as well as between governments and sectors of civil society based on common understanding of shared interests and needs."

The meeting resulted in '*The Rio Declaration on Environment and Development*'; the adoption of Agenda 21 – a '*programme of action for the 21st century*'; the creation of the Commission for Sustainable Development (CSD); and the adoption of conventions on '*Protecting Species and Habitats*' and '*Climate Change*' [30]. Arguably, the most important product of the meeting was the adoption of Agenda 21, a sizeable document with hundreds of recommendations for action (Agenda 21 and its 'means of implementation' span four out of the five volumes of the conference proceedings).

2.2.6 The Union of Concerned Scientists

Another key milestone in environmental awareness was the 'Warning to Humanity' issued by The Union of Concerned Scientists (UCS) in November 1992 [31]. They appealed to the world's leaders and people to take immediate action in halting irreversible damage to global life support systems. This warning was made by some 1,700 of the world's leading scientists including a majority of the science Nobel laureates. The warning records damage already made to the Earth's air, water & oceans, soils, forests and living species. The warning included a statement that:

> "a great change in our stewardship of the earth and the life on it is required, if vast human misery is to be avoided and our global home on this planet is not to be irretrievably mutilated."

The UCS Chairman Dr. Henry Kendall stated [32]:

> "this kind of consensus is truly unprecedented...there is an exceptional degree of agreement within the international scientific community that natural systems can no longer absorb the burden of current human practices. The depth and breadth of authoritative support for the Warning should give great pause to those who question the validity of threats to our environment."

2.2.7 The Worldwatch Institute

The Worldwatch Institute (WWI), founded in 1974, is a research organisation that focuses on the relationship between the global economy and natural resources. The WWI is responsible for a number of publications, most notably the annual reports *State of the World*, and *Vital Signs*. The *State of the World* report is referred to by governments, UN agencies and policy makers and has been published every year since 1984 [33].

In *State of the World 1998*, Brown and Mitchell report that [34]:

> "As the world economy has expanded nearly six-fold since 1950, it has begun to outrun the capacity of the Earth to supply basic goods and services". They continue that "...despite the many collisions with the Earth's natural limits...we continue to raise our consumption levels as though the Earth's capacities were infinite."

2.2.8 Earth Summit +5

Five years on from the Rio summit the "Earth Summit +5" was held in New York 23-27 June 1997. This followed 2 months of review work on progress since the Rio summit [35]. The summit ended with apparently few commitments, but according to a UN review, with at least one agreement that [36]:

> "five years after the Rio Earth Summit, the planet's health is generally worse than ever."

A UN publication of June 1997 reports that "business-as-usual is not likely to result in sustainable development," and further noted that [37]:

> "Gaps between the rich and the poor continue to grow...over 1.1 billion people – 20 per cent of the world's population – live in absolute poverty."

> "Twenty per cent of the world's people continue to consume eighty per cent of its resources."

> "Forest loss continues at an unacceptable rate. A total of 13.7 million hectares of forest...are cut or burned each year."

> "One fifth of humanity lacks access to safe water."

2.2.9 World Summit on Sustainable Development

The UN world summit on sustainable development in Johannesburg 2002 was intended to review progress since Rio and also focus on problems of developing countries, particularly poverty [38]. Success of the summit was mixed, with some calling it a flop even before it had taken place [39]. Outcomes included:

- Reaffirmation of commitment to full implementation of Agenda 21
- Various individual partnerships between governments, business and civil society
- The political declaration 'The Johannesburg Declaration on Sustainable Development'
- A negotiated 'Johannesburg Plan of Implementation'

Despite the successes, general political consensus on key issues such as energy and transport was weak – for example there was no agreed target for renewable energy use. Even more critically – beyond the talks, successes and failures, *actual* progress in the 10 years since Rio is considered meagre [40].

2.3 Consensus of Opinion

There is a strong consensus of opinion among world-leading scientists and prominent organisations that:

- humanity may only have a few decades – or less – left in which to reverse the current exploitation of the earth; and
- without reversing this exploitation, humanity faces an unprecedented decline in human population, and considerable world-wide misery.

Even if generous allowance is made for uncertainty, it seems clear that humanity faces a situation of considerable danger and that this has been known for some time. But Brown *et al* note that [41]:

> "the two decades since the Stockholm conference have seen only scattered success stories".

Furthermore, the Worldwatch Institute reports many failures including [42]:

- most of the world's fisheries are at or beyond capacity – one third of which are threatened with extinction;
- water tables are falling on every continent (this has implications for availability of water for food production through irrigation);
- forest cover is continuing to disappear world-wide (which has many implications including flooding and soil erosion);
- water pollution is "spiralling out-of-control" in developing countries where "industrialisation is proceeding at a record rate but without adequate controls." This includes pollution of water used for irrigation of crops.
- more than 1000 of nearly 10,000 known species of bird are threatened with extinction;
- nearly 1,100 of the world's 4,400 species of mammals are threatened, including half of the world's primates.

Statistics such as those presented by the UN and the Worldwatch Institute are evidence of something profoundly wrong with ways in which humankind is living and managing, or failing to manage, the natural environment. These figures represent a critical failure to take seriously the call for action by the UCS (and others) and a failure to adopt the recommended strategies.

The grave implications of this evidence poses several questions including:

- Why is it that sustainability is not "the overriding goal and test of national policy and international co-operation" that the WCED called for?
- Why are the principles of sustainability not taught in our schools and appearing daily on our television screens?
- More critically – in the context of this thesis – why is sustainability not already the explicit, ultimate goal of all environmental management effort and the application of tools including LCA?

2.4 Reluctance to Act on Sustainability

It would be grossly unfair to countless individuals all over the world to suggest that **nothing** is being done about sustainability. However there are serious barriers to progress. These include:

- materialism
- expansionism and the current system of national accounts
- ignorance
- pain
- lack of political will.
- the business dilemma (defined in 2.4.6)

These issues are discussed in the following sections 2.4.1 – 2.4.6.

2.4.1 Materialism within the Developed World

The UN report that some 80% of material world resource consumption is being made by only 20% of the world's population [43]. This observation is evidence of a massive divide in material wealth within the global population. Humans have a natural desire to acquire possessions, and in modern society material wealth is often associated with status. Systems of national accounts (see 2.4.2) are merely a convenient, though inadequate, way of expressing how well this desire is met – even though it is questionable to what degree material goods satisfy all our welfare needs [44] (see 3.4 Welfare & Economics). Addressing consumption and related issues challenges accepted ways of life – particularly in the developed world. Fortunately, some countries have already committed to tackling the issue of consumption: Austria has included a 'factor 10' (90 percent reduction) in its environmental policy, and the OECD has expressed interest in such radical reductions [45].

2.4.2 Expansionism & Systems of National Accounts

Progress towards sustainability is incompatible with much of the modern-day drive for 'better' lifestyles, increased production and economic expansion. Industry could be in the business of increasing world-wide welfare through sound stewardship of products and the natural resource base. Instead, business must respond to the prevalent economic drivers and is therefore promoting unsustainable behaviour [46]. Business is often about short-term wealth creation and economic growth, not the provision of sustainable products and services in a given market. Despite the calls to action made at the earth summits and similar events, the world economy continues to expand [47] in an unsustainable way. This presents difficulties for governments, businesses and organisations that are trying to adopt more sustainable policies by promoting and rewarding sustainable behaviour.

The expansionist ethic is typified by governmental systems of national accounts (SNA) which ignore new economic thinking [48] where environmental depreciation is taken into account. SNA were adopted by many countries in the years following the Second World War and include economic indicators of a country's 'health' such as gross national product (GNP) [49] or gross domestic product (GDP). The SNA ignore stock levels of natural resources. They actually exacerbate the environmental crisis, *encouraging* depletion of both renewable and non-renewable resources by formally recording resource exploitation as a credit labelled 'production' [50].

Daly and Cobb have proposed a new measure of progress that builds on attempts by others to find an alternative to GNP: The Index of Sustainable Economic Welfare (ISEW). This was first published in *For the Common Good* in 1989, and republished in 1994 after a number of revisions to the index [51]. The ISEW and other indices such as The Genuine Progress Indicator (GPI) [52,53] have brought the failures of SNA to popular attention. Indeed, the UK's Prime Minister, Tony Blair has acknowledged such failures [54]:

> "focusing solely on economic growth risks ignoring the impact – both good and bad – on people and on the environment... there is a growing realisation that real economic progress cannot be measured by money alone".

The above represents a departure by the UK government from measuring the country's health or 'success' by traditional methods alone. The government has produced a list of economic, social and environmental indicators, including 15 'headline' indicators –

including GDP – with which they intend to measure the nation's progress on sustainable development [55].

Jackson, Marks, Ralls and Stymne revised and presented the UK ISEW [56], but Jackson warns that – like GDP – the index uses consumer expenditure as its basis [57]:

> "the statistical foundation for the ISEW is still the level of consumer expenditure; disposable income is still regarded as the basis for well-being; ... the same assumption still rests at the heart of [UK] Government policy."

> "Increasing the level of consumption remains the single most important political and social goal. Though tempered perhaps by the injunction to account for the environmental and social costs of consumption, Blair's position – and indeed the position of the ISEW – is to maintain the centrality of consumption as the building block for quality of life."

Elsewhere, Jackson is more blunt about the issue of consumption [58]:

> "what characterises the development of the industrial economy, and perpetuates the myth of the success of the consumer society, is the assumption that all human needs can be satisfied through material goods."

But does increased consumption, encouraged by traditional accounting methods, really deliver *welfare*? Not according to Max-neef [59]:

> "for every society there seems to be a period in which economic growth (as conventionally measured) brings about an improvement in the quality of life, but only up to a point – the threshold point – beyond which, if there is more economic growth, quality of life may begin to deteriorate."

Max-neef reports that the UK and the US passed this threshold in the 1970s, with other European countries following in the 1980s. It would seem, then, that pursuit of ever greater economic growth and materialism is not just damaging to the environment: business as usual is having a negative effect on quality of life in the 'developed' world.

Consumption and its links to welfare are further discussed in section 3.4 Welfare & Economics.

2.4.3 Ignorance

Personal priorities affect judgement and often lead to unsustainable actions. Across the world people have different concerns and different levels of concern. Meadows *et al* discuss common perspectives of the world's people [60]. Some humans, particularly those in industrialised countries, can enjoy the luxury of dwelling on concerns that do not affect their immediate surroundings or point in time. But as Meadows *et al* write, for most people [61]:

> "[life] is very difficult, and they must devote nearly all of their efforts to providing for themselves and their families, day by day."

Some communities in the developing world had sustainable practices until western-world economic growth was imposed on them (indeed this is not a contemporary problem: Ponting describes the devastating affect of European expansion on hitherto sustainable communities in Madeira and the Canary Islands in the fifteenth century [62]). For the majority of the world's people, consideration of sustainability is irrelevant to the temporal and spatial frame within which they have to operate to survive. Of course, for many in the developed world, life is not nearly as harsh. But there is a natural tendency to be more concerned with our immediate families and friends than with national concerns. We are also – as individuals – often more concerned with the more immediate future, than about where we may be in ten years time. For example, keeping a job is important because most of us need the income to ensure we can satisfy even our most basic needs; career development for most people is a secondary issue (basic needs are further discussed in 3.4.1).

Many concerns about sustainability are however those of a global nature, possibly decades into the future. It is perhaps not surprising that many people – even those in developed countries – do not understand (nor even want to understand) paradigms of sustainability. The concerns appear to be remote and beyond their experience and influence.

There may be other reasons for ignorance of the fundamental issues of sustainability among people who enjoy material wealth. To a large extent ignorance can also be attributed to a lack of – and could therefore be mitigated by – education, both in and out of the classroom [63,64]. Brown, Flavin and Postel suggest that while [65]:

> "environmental awareness has reached new heights in the nineties…the world has a long way to go in raising environmental literacy to the point where the process of reform becomes self-sustaining."

Others, who may have deep ecological or social *concern* may themselves not understand the full effect of our lives on the planet [66].

In summary, there are very different ways in which people are ignorant of the challenges of sustainability.

2.4.4 Pain

Having to confront deep moral issues is painful and difficult. This is especially true for many of those that must take responsibility for the changes in their behaviour required for a more sustainable world. Taking a lead can quickly result in a sense of having the world's problems on your shoulders. In *The Limits to Growth*, Meadows *et al* say of their own conclusions [67]:

> "we are quite frankly overwhelmed by the enormity of the job that must be done".

Wackernagel and Rees write succinctly [68]:

> "acknowledging this sustainability challenge is psychologically disturbing."

2.4.5 Lack of Political Will

Lack of political will probably results from a blend of pain, ignorance and a fear of the loss of short term welfare. Like other people, politicians have their own hopes and fears, and simply may not have the degree of environmental literacy to understand the scale of the world's environmental problems. Governments can only effect changes while in power and are likely to be concerned about the unforeseen impacts of introduction of radical changes; and change may so upset voters that they might lose office. In implementing global environmental policy, governments are understandably keen to remain competitive against those countries that fail to act on environmental issues. Indeed for small countries to act while large economies fail to do so can feel like, and often will be, a futile gesture except to exert moral pressure.

2.4.6 The Business Dilemma

Businesses face a dilemma [69]: they are under ever greater pressure from stakeholders and legislation to improve their environmental performance, yet the prevailing economic system and the need for profitability seems to totally contradict this. The resulting response is to become as "green" as possible, using the latest techniques tools and approaches, but the approach is inevitably 'at least cost' to profit or in pursuit of an obvious payback. This leads 'practical' trade-off (e.g. BATNEEC/BPEO*) and an inability to embrace sustainable development in practice. 'Justifying' environmentally damaging activity in this way has led to a stagnation of effective activity. Welford has referred to this business way of surviving increased environmental pressures as 'eco-modernism' [70].

2.4.7 Barriers to Progress

The barriers to progress discussed in sections 2.4.1 – 2.4.6 allow deterioration of the natural environment to prevail more or less unquestioned. Even where there is genuine

* Best Available Technology not Entailing Excessive Cost (BATNEEC) and Best Practical Environmental Option (BPEO) are approaches to pollution abatement which include financial and economic considerations. Best Available Control Technology (BACT) is an example of a similar concept, but free from financial/economic considerations.

concern about environmental issues there remains misunderstanding about the magnitude of the deepening environmental crisis. Many people do not fully appreciate the nature of the issues involved through lack of education. Some perhaps do not want to acknowledge the implications of sustainability because the issues seem irrelevant to their personal way of life. Others are trapped in their activities by unsustainable economics. Yet, whether through lack of education, the business dilemma, or the difficulty of trying to grasp the issues of sustainability, there remains an air of 'business as usual' as the UN have noted (see page17).

2.5 Momentum for Change

There is some good news despite the doom and gloom of environmental problems and the reluctance to act on them as discussed above. Increased awareness of the issues facing mankind has inevitably led to increased knowledge about how to approach solving them. Frankel describes 4 'eras' of environmental awareness paraphrased below and the corresponding response of industry [71]:

- First era of 'compliance' where corporate response was 'reactive' (1970s)
- Second era 'beyond compliance' where corporate response was 'anticipatory' (1980s)
- Third era of 'eco-efficiency' where corporate response was more 'pro-active' (1990s)

Frankel suggests we are ready to enter a fourth era – one where 'design for the environment' (DfE) or 'design for disassembly' takes place; with closed material loops and business based on service rather than material product [72]. Clearly, not all of industry has picked up this pace – as Nattrass and Altomare point out [73]:

> "In the era of eco-efficiency…there are countless organisations that are just beginning to consider what it means to move beyond compliance, and countless others for whom environmental management still means mere compliance with the law."

The key factor is that the economic framework within which businesses operate must encourage, rather than antagonise, development beyond regulatory compliance. Without this, the new drive for positive change will likely fail to gather momentum.

2.6 Conclusions

Sub research question (a) asked:

> **What are the fundamental issues that determine the need for environmental management tools including LCA?**

In short, there is a need to reverse current trends in consumption of, and damage to, the natural resources that support life.

Lifestyles enjoyed by the materially wealthy (the minority) do so at the expense of *billions* (the majority) of poor people and threaten the livelihood of future generations. Moreover, there is a consensus of opinion among prominent scientists and respected organisations that we are in the midst of an unprecedented environmental crisis and that we must act quickly to avoid irreparable damage to the earth's natural resources and systems. Yet, instead of seeking to reverse the harmful trends to life supporting systems, the behaviour of the 'developed' world in particular encourages further destruction at an ever-increasing pace.

The concept of sustainability, brought to popular attention by the WCED, establishes a more positive focus by introducing a goal for a better future, living within the constraints placed by nature. Moreover, this sustainability has social as well as environmental dimensions. Chapter 3 develops a qualified definition of sustainability for the purpose of providing a more practical response to sub research question (a).

Chapter 3 - What is Sustainability?

3. Objectives

The objective of this chapter is to develop a qualified definition of sustainability, for the purpose of providing a more practical response to sub research question (a), and to provide a means with which to review LCA methodology in part II.

3.1 Introduction

Chapter two covered the history of recent environmental concern; the consensus reached by many prominent organisations that humankind must take responsibility for the increasingly perilous situation that it faces; and discussed evidence supporting this position.

In contrast to this general view of 'crisis', the concept of sustainability brought to popular attention by the WCED provides a much more immediate and positive focus. This chapter explores the issues of sustainability and develops an operational and qualified definition.

3.2 Paradigms of Sustainability

3.2.1 Sustainability or Sustainable Development?

Introduction to the subject of sustainability is difficult in part due to the terms 'sustainability' and 'sustainable development' being used interchangeably. The difficulty is compounded by the ambiguity of the phrase 'sustainable development [74,75]. Some might assume that the term 'development' means 'economic growth' but it has a much broader focus than just economics and is intended to include 'quality of life' [76] and the satisfaction of welfare needs.

There is a need for greater clarity about sustainability within the field of environmental management and other disciplines. There is a need for clarity *per se* because of the risk of confusion, but – more seriously – the failure to understand and effectively communicate sustainability issues impairs the ability to act decisively [77].

In this thesis, sustainable development is defined as a system for the meeting of needs in a way that could go on forever, and the state of sustainability is the result of sustainable development achieved globally.

The term *sustainability* is therefore used to describe the broadest goal and *sustainable development* describes this goal applied at a more local and specific scale (such as a process, company or nation). This chapter develops its own definition of sustainability in an effort to promote greater clarity about what sustainability means within the context of this thesis. The objective is to form a definition that is both concise and comprehensive and go as far as is possible to eliminate the opportunity for confusion in interpretation. This definition should also aid the operationalisation of measures towards sustainability and will provide a context within which LCA work can be examined.

The most popularly referenced definition of sustainable development follows the Brundtland definition [78]:

> "Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

While the Brundtland definition of sustainable development is certainly popular, there is no one commonly accepted definition. Pearce *et al* list some 23 definitions in *Blueprint for a Green Economy* [79], and Murcott of the Massachusetts Institute of Technology revised the list of Pearce *et al* (and others) and drew up a total of 57 different definitions of sustainable development [80]. Pezzey records sixty such definitions [81].

The UK Government definition of sustainable development, while slightly more vague reads [82]:

> "ensuring a better quality of life for everyone, now and for generations to come."

There is a reasonable consensus that sustainable development points to a moral imperative to cater to the needs of those alive today without impeding future generations' chances of the same. However, definitions such as those presented by Brundtland and the UK government provoke as many questions as they provide answers. For example, how are we to distinguish between wants and needs? Whose life do we mean? Just those of us in developed countries? Are we only concerned with mankind and not other species? Unfortunately the answers are not clear-cut.

Despite sustainability as a subject matter being complex and treacherously subjective, the overwhelming question is 'how is sustainability to be achieved in practice?' This question requires some elaboration of the conditions that must be satisfied and it is this qualified definition that is developed here.

3.2.2 Social, Economic and Environmental Paradigms of Sustainability

Sustainability as a concept is wide-ranging, encompassing far more than environmental or ecological issues. To make the matter more manageable, the subject is often differentiated between economic, social, and environmental domains. Indeed, some authors appear to discuss these three areas as if they were independent challenges [83], but it is difficult to envisage significant progress being made in any one domain of sustainability to the exclusion of others. Indeed, the requirement that all three domains are properly accounted for is central to the 'triple bottom line' (TBL) [84] which has imposed itself on more traditional business reporting. However, simply reporting on the three domains, or using a more appropriate formal framework such as the triple bottom line, still does not describe the goal of sustainability nor operationalise it by describing how it is to be achieved.

The sustainability concept is often depicted pictorially as three intersecting circles of social, economic and environmental objectives [85] (see Figure 4). The intersecting circles model tends to look like a Venn diagram and imply that the delivery of social, economic, and environmental goals will deliver 'true' sustainability at the point where these three features (circles) overlap. This overlapping region correctly suggests that all three domains have to be ultimately satisfied, but this does not mean that all efforts towards sustainability are required to be balanced between these three domains. This model does not reflect the fact that the economic domain is wholly dependent on the other two (see later) and is therefore somewhat ambiguous. Of the economic, social and environmental aspects of sustainability it is the environmental issues that are the most fundamental and it is prudent that this be reflected in such a diagram. It is **the natural environment** that supports societies and economies [86,87]. Put another way, the environment can survive without human societies and economies, yet economies and societies cannot survive without the environment's resources. Economic advantage has to be based on sustainable activities which operate within the constraints of society and nature. Furthermore, economic mechanisms must *promote* sustainable activities which then deliver a sustainable economy.

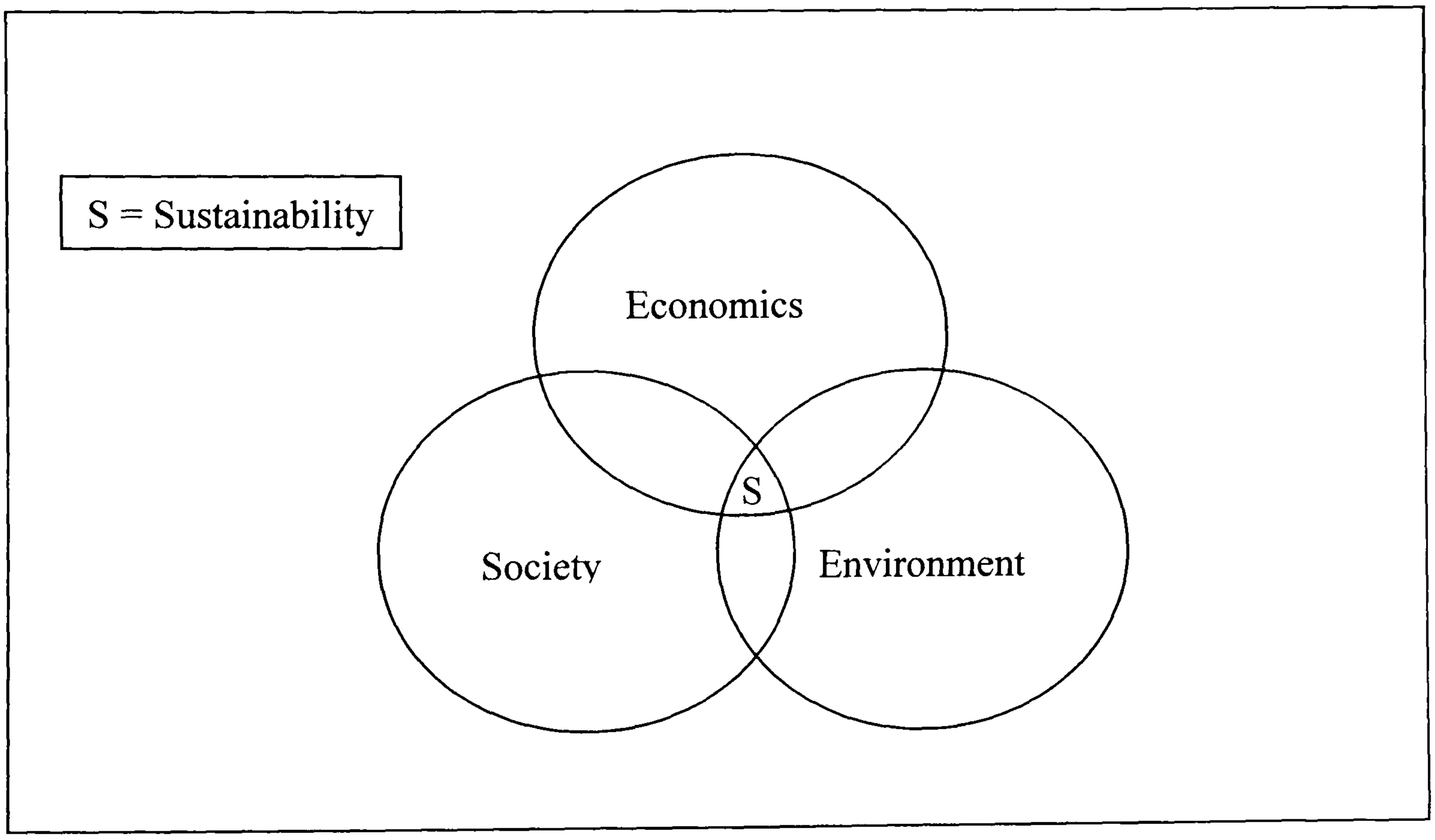


Figure 4 - Intersecting Circles Model

In the developed world, humans tend to see themselves as somehow emancipated from, or in control of, the natural environment. This perception is unhelpful as it makes it harder to see problems. Yet this kind of thinking is perhaps encouraged by the intersecting circles model. What is more, interpreting the three domains as requiring equal attention encourages thinking about the continued 'practicality of trade-off' which arises directly out of the business dilemma (see page 25) and its BATNEEC solutions. Trade-offs – although unavoidable due to the conflict between economic and environmental 'reality' – may nevertheless prove unsustainable. The social and environmental resources which underpin economic activity cannot be sustainably traded-off against economic gain unless their supply is not threatened or can be remediated in an appropriate way.

A more accurate model than the 3 intersecting circles approach is to consider sustainability from environmental and socio-economic perspectives (see Figure 5).

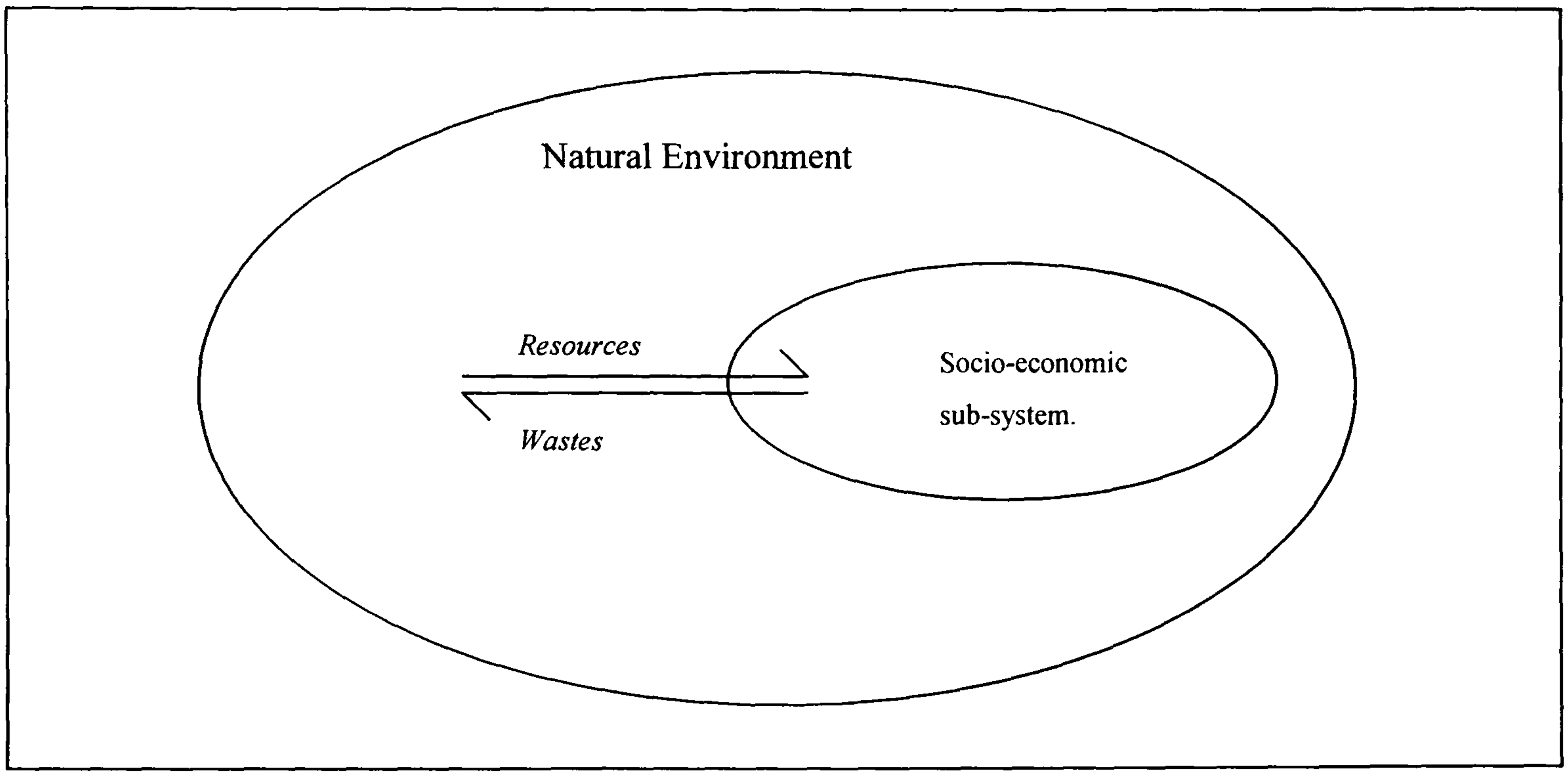
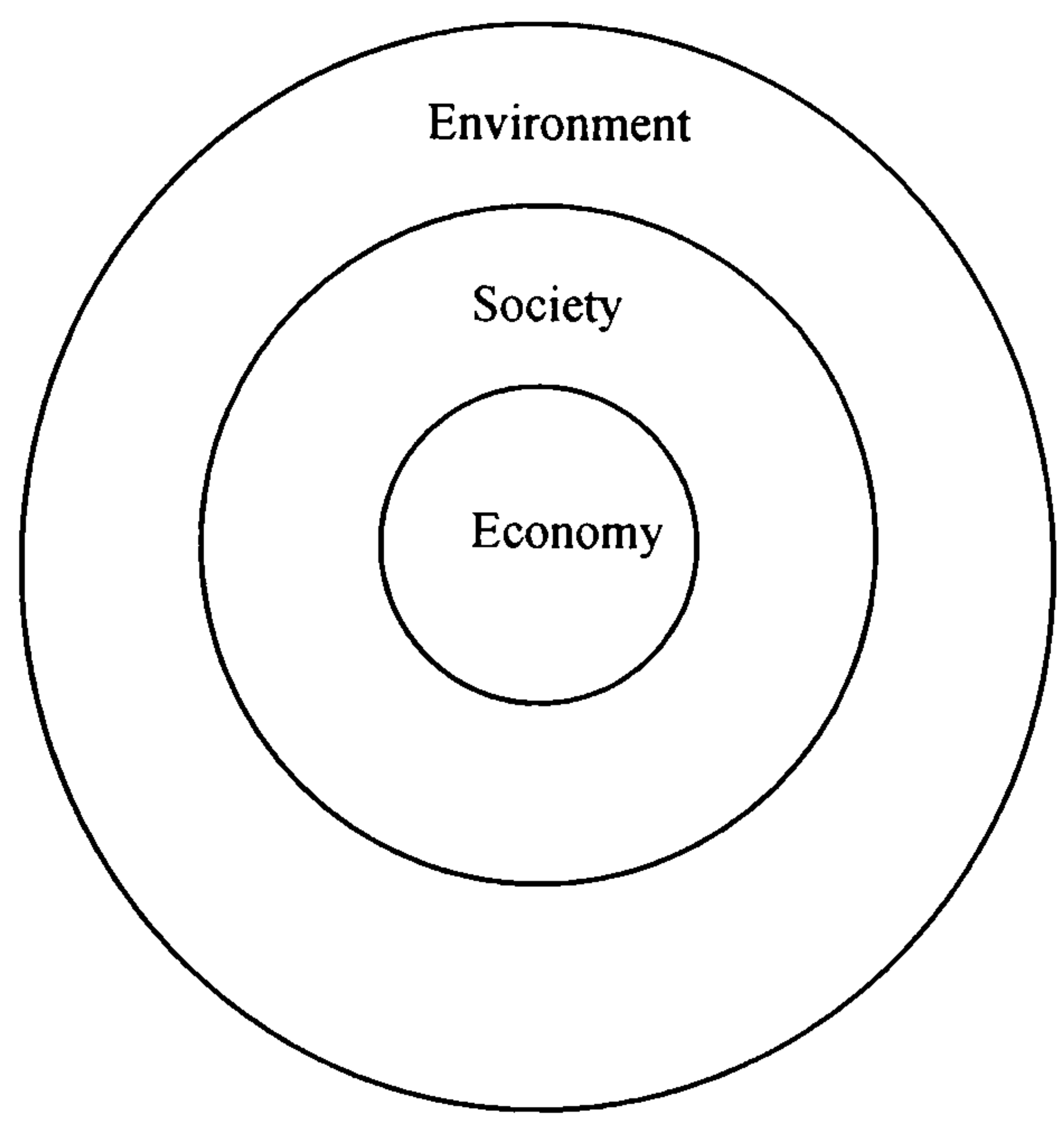


Figure 5 - Relationship between the Environment and the Socio-economic System

A model such as Figure 5 is consistent with that presented by Reid [88] during a discussion of *The Limits to Growth.* The diagram Reid uses actually goes further in that it represents the environment as a thermodynamically closed system (such as is presented in Figure 12 on page 45). Since 'economy' is a construct of society it is possible to go further still. Levett makes this very point and re-defines the 3 intersecting circles model as concentric circles or 'Russian dolls' [89] (see Figure 6) :

> " 'The economy' is not an end in itself or a force of nature. It is a *social* construct. It only works as it does because human societies have created the institutions, and inculcated the assumptions, expectations and behaviours which *make* it so".

Levett's model is fundamentally different to the intersecting circles model (Figure 5 above). Whether or not the intersecting circles model is intended to imply a balance of social, economic and environmental goals – or something else entirely – the concentric circles model helps illustrate unequivocally that the economy is 'within' society, and that society must live within the limits of the environment.



Adapted from Levett [90]

Figure 6 - Concentric Circles Model of Sustainability

The revised models as presented in Figure 5 and Figure 6 underline the realisation that a separatist view of mankind somehow emancipated from – and in control of – the natural environment is unrealistic. Society is itself an implicit part of – and therefore constrained – by the natural environment. The degree to which mankind must change its 'anthropocentric' attitude (see Figure 7) toward the environment forms a natural target for debate.

Dunstan and Swan write that mankind must [91]:

> "Cultivate biocentric rather than anthropocentric views and attitudes regarding other Beings and Nature. The conceited notion that humans stand at the center of the universe, and all things are given value based on our utilitarian needs must be rejected. All species and Beings have

intrinsic value and worth, and must be allowed their own potential, whether we understand them or not".

The comments of Dustan and Swan are from a position often termed 'deep ecology' (see Figure 7) which, although extreme, represent a more involved and realistic viewpoint than contemporary thinking or 'shallow ecology' [92] where business concerns often comes before and at the expense of environment.

Anthropocentric [93]: "Regarding human beings as the central feature of the world; interpreting environmental and resource issues solely in terms of human values and standards".

Deep ecology [94]: "A perspective that recognises an inherent right to existence among all living organisms and which sees humans as not more or less important than any other species".

Source: Gilpin, *Dictionary of Environment and Sustainable Development*

Figure 7 - Definitions of 'Anthropocentric' and 'Deep Ecology'

Taken to its extreme, deep ecology represents conservation for its own sake – this lies at the other end of the spectrum to pure anthropocentricism. A compromise between these viewpoints would leave more room for manoeuvre in the pursuit of sustainability and sustainable development. Clark and Kozacek describe such a position as 'ecocentric' [95]:

> "Ecocentric, 'in the middle' of the anthropocentric-biocentric continuum."

There is much to the anthropocentric-biocentric debate in the literature and – like sustainability itself – a great range of interpretation of what these philosophies or words mean. What is important to take from this debate – in the context of this chapter – is that irrespective of whether an individual regards nature as having intrinsic value, it must be allowed to sustain itself in order to sustain mankind. Put another way, irrespective of how far along the anthropocentric-biocentric continuum (as Clark and Kozacek put it) an individual's philosophy lies, the survival of both nature *and* mankind depends on the 'availability' of nature (see Figure 8). Note that resources critical to both nature and humans are explored in section 3.5.2 Defining Life Supporting Resources.

The different philosophies discussed above clearly have an impact on the debate surrounding the degree of change required in order for sustainability and sustainable development to be a reality. These philosophies are also represented through the notions of 'strong' and 'weak' models of sustainability which are explored in the following section.

Note that in this thesis, the term 'availability' used when discussing resources is to reflect both the quantity and quality of a resource. It is both of these elements that make a resource 'available' to fulfil a function or value, not quantity alone. In addition, any damage to, or net consumption of, a resource is defined here as a *Resource Availability Infringement* (RAI). This is a simple, yet useful way to think of damage or loss of resources. Whether by pollution, over consumption, loss of access and so on – the net effect has been the same: loss of availability of that resource.

The concept of RAI has been further developed at Heriot-Watt University to include a pictorial depiction of links between anthropogenic processes and RAIs [96] (see page 168).

Figure 8 - Resource Availability Infringement

3.2.3 Weak *versus* Strong Sustainability

'Weak' and 'strong' models of sustainability are used within the sustainable development literature – primarily by economists – to debate the *degree* of required change to meet the challenge of sustainability; the debate is analogous to eco-philosophy debate discussed above.

Van Dieren *et al* discuss *weak*, *sensible*, and *strong* and *absurdly strong* sustainability [97] (note that the term 'capital' is used by Van Dieren to reflect 'wealth' in a wider sense than simply financial wealth):

* *Weak* and *sensible* sustainability essentially assumes that main groups of capital – i.e. natural, man-made, social and human capital – are interchangeable and merely requires that the sum total amount of capital be conserved.

* *Strong sustainability* goes further and demands that while the individual amounts of capital are maintained separately – i.e. they are not substitutable – the net total for each group must remain the same. This is in line with the thinking presented in this thesis. Van Dieren *et al* give the example that 'for natural capital, receipts arising from depleting oil reserves should be invested in ensuring that energy will be available to future generations'. Strong sustainability encompasses the notion that the natural environment carries out some function that cannot be otherwise carried out by or somehow substituted for in the technosphere – photosynthesis for example, or protective stratospheric ozone.

* *Absurdly strong sustainability* does not allow non-renewable resources to be used at all.

To forego the use of a resource for the sake of conservation is a position of extremist environmentalism or conservationism. What is crucial is that a given resource is used in a responsible manner:

1. environmental resources should be employed in such a way as to avoid unnecessary or irreversible harm to the quantity and quality of other natural resources and services;
2. if the quantity of a given stock is under threat, alternative types of resource and required technologies should be found and adopted in sufficient time to ensure a smooth transition period. Note that some resources may not have an obvious alternative, so their use must be exercised with an appropriate restraint.

In conclusion sustainability requires an eco-centric attitude which acknowledges the secondary role of the economy and the notion of strong sustainability [98]. Substitution – which underpins weak sustainability – is a matter of economic convenience [99] and should be discouraged.

Definitions of sustainability (and sustainable development as an agent of sustainability) such as offered by Brundtland or the UK government introduce the need to conserve sufficient resources for future generations, rather than just the present. But such definitions do not always help visualise the discipline – and sometimes the urgency – imposed by the goal. Section 3.3 below develops a more prescriptive definition of sustainability that will better articulate what is required.

3.3 Defining Elements of Sustainability

The remainder of this chapter develops an operational definition of sustainability. The objective is to produce a definition that is detailed enough to carry precise and practical meaning while remaining concise.

Development of the definition of sustainability will begin by paraphrasing the Brundtland statement (Figure 9). This definition, like many, has two key requirements: the meeting of needs (social or 'welfare' needs) and the temporal dimension of intergenerational equity (that implies the natural environment should be left to tomorrow's generations so that they are no worse off than the present). A third – spatial – dimension is also implied: meeting the needs of all present today, not just selected communities. Even with these key elements included, the definition is not an operational one since it does not identify the elements that need to be put in place.

Sustainability is a state of the world which meets the needs of the present and of the generations to come.

Figure 9 - Basic Definition of Sustainability Based on Brundtland

In order to broaden the definition it is proposed to include three key areas:

- welfare and economics (section 3.4), because the state of sustainability is strongly related to need satisfaction

- limits to the use of natural capital (section 3.5); and
- maximising the availability of natural capital (section 3.6) because the survival of both nature and mankind depend on the availability of nature.

3.4 Welfare & Economics

3.4.1 On Meeting Needs

The concept of environment within environmental management has broadened to mean both social and natural environmental features (see for example the definition of environment in ISO 14001) [100]. Evidence of this shift is the recent growth in importance of corporate social responsibility and triple bottom line reporting.

Well-being or welfare is a state delivered by the satisfaction of wants and needs [101]. Meeting material needs such as water, food and shelter, are vital to life. Thus there is a need for a clean environment supplying a consistent flow of resources, and an ability to make a living to gain access to the same. Beyond physical survival we have other needs and desires, such as a need to remain healthy – in mind body and spirit – and to function as communities. Maslow is well known for his work in the field of human behaviour, proposing a hierarchy of needs that motivate human behaviour [102, 103]. In Maslow's model, the higher 'growth' needs (self actualisation) are not met until the lower level needs are satisfied. At the bottom of the hierarchy are the most basic material needs, such as food, water and physical security. The other needs are all met by non-material fulfilment.

It is clearly important from the perspective of sustainability that there are sufficient material resources that meet the most basic needs. There are many luxury goods available to those in the developed world that – while they can make life more enjoyable – stretch way beyond the Maslow definition of material need, but at the same time fail to meet the higher social needs of belonging, esteem and self-actualisation. Without such social needs being met, individual communities become dysfunctional and ultimately unstable.

3.4.2 Economy and Welfare

The industrial economy seeks to 'match supply to effective demand for goods and services in an efficient manner and to an acceptable quality' [104], but it does so based on the assumption that such output can satisfy **all** human welfare needs [105]. Furthermore, output of the economy is not always the desired good and services. Indeed the economy – constituent processes or ways of doing things – contributes in both a positive and negative way to welfare through the outcomes (outputs and effects) of its processes. Its desired outcomes – goods and services – have been sometimes overshadowed by the undesired side effects of pollution, poor health and all manner of socio-environmental degradation effects. Sustainability is therefore affected both positively and negatively by the economy. Ekins and others have related 'goods' and 'bads' from the economy to ecological and human 'capital' [106].

We learn from Maslow that not all needs are material in nature and from Max-Neef (see page 139) that it does not necessarily follow that increased material consumption – through consumer expenditure – guarantees welfare. Indeed, Jackson concludes in his book 'Material Concerns' that [107]:

> "Offering sanctity of choice, fulfilment of our desires, and the greater good of our fellow beings, [the industrial economy] has delivered environmental destruction, economic instability and new, alarming kinds of poverty: poverty of identity, poverty of community and poverty of spirit."

A world economic system basically geared to exploitation including imbalanced trade and debt between the north and the south leads to mass loss of natural capital, poverty and human suffering in the developed world [108]. Even in the developed world, the economy is not delivering welfare. Material throughput is way beyond the acceptable level in the Maslow requirement, and it is perhaps not surprising that there is a growing 'voluntary simplicity' movement in the US (it even has its own journal [109]).

For many of those in the developed world there is the at least choice between material profligacy or 'voluntarily simplicity' which many find a more fulfilling lifestyle. But what of trans-national, inter-generational and inter-economic equity? Sustainability demands that citizens of the 'developing world', and the unborn generations of tomorrow all have at least an equal chance of their needs being met let alone choices over the degree of materialism they wish to have. Maslow's definition of (material) need will be less than the vast material throughput of a typical developed world economy.

Developing countries and their citizens have no less of a 'right' to enjoy material plenty than their wealthier counterparts, but there is already evidence that material consumption is threatening natural systems that support life. Rich and poor societies are all affected and must therefore work together to understand in a holistic way how to move forward in a sustainable manner – certainly featuring material consumption at more sustainable levels by wealthier nations. Those in wealthy societies should re-consider their value systems, and recognize that – without change – their lifestyle is at the expense of a trans-national or intergenerational equity and involves a vast material throughput. The notion that economic 'growth' and 'wealth creation' are inherently good features of society must be examined, while the effect on welfare and on environmental and social costs has to be taken into account.

3.4.3 Measuring Welfare

Having argued the case for trans-national and intergenerational welfare, it would seem appropriate to find a measure of welfare with which to monitor progress. To this end, Daly and Cobb presented the Index of Sustainable Economic Welfare (see page 21). They themselves note some problems in measuring welfare as a whole [110]:

> "In measuring welfare one cannot avoid to a large extent implicitly defining the concept by one's very measure of it."

The ISEW is not so much a comprehensive measure of social welfare then, but it does at least provide a measure of the positive contribution of the economy to it. Complaining of the inherent subjectivity of attempts to measure welfare (including the ISEW), Levett writes [111]:

> "we are probably even further from satisfactory measurement of quality of life than we are with environmental limits."

Even though laden with value choices, we can take some comfort from the fact that the various attempts at measuring economic welfare over the last few decades have at least shown similar trends. Trends which unfortunately have tended downwards for even 'developed' countries [112].

Levett suggests – since subjectivity is unavoidable – that people should be consulted on what they think welfare is [113]. To this end The World Game Institute (WGI), based in Philadelphia, have gone to great lengths to find an improved understanding of what a better tomorrow could look like. The WGI's 'What the World Wants Project' is based on answers to a question put to over 200,000 people from school children to government leaders and corporate executives. They were asked [114]:

> "Given the present situation of the world, what do you want the world to be like twenty years from now? What is your preferred state?"

The WGI report that:

> "One of the early surprises of this effort was the unanimity of the preferred state vision that resulted. Whether the participants were government leaders from Malaysia or students from Maine, Motorola executives or Japanese Junior Chamber of Commerce members, they all came up with something very similar."

The answers to the WGI's visionary questions led to the WGI's definition of 'The Preferred State' [115] (Figure 10). While this vision is useful in understanding what people's desires for a better tomorrow are, it certainly does not lend itself to achieving quantifiable indices such as the ISEW or the Genuine Progress Indicator (GPI) [116,117]. There are published guidelines [118,119] on selecting local community indicators of welfare, but the ISEW and GPI remain the most comprehensive macro measures of welfare available at present. It is also important to remember that indices like ISEW and GPI are measures of the level of positive contribution of the economy to welfare, rather than of – seemingly un-quantifiable – welfare itself.

100% of humanity has, on a sustainable basis:

- Abundant supplies of nutritious and culturally appropriate food.
- Abundant supplies of clean water.
- Adequate housing.
- Local comprehensive healthcare.
- Healthful sanitation facilities.
- Abundant, clean, safe and affordable supplies of energy.
- Employment opportunities and fulfilling work.
- Vocational alternatives and on-the-job-training.
- Literacy and access to advanced educational opportunities.
- Access to communication facilities so that anyone can communicate with anyone else on Earth who wants to be communicated with.
- Access to transportation facilities, enabling anyone to go anywhere.
- Access to decision-making processes that affect their lives.
- A peaceful, secure, nuclear/chemical/biological weapon-free world.
- A crime- and drug-free world.
- A clean, self-regenerating environment, free of toxic wastes and pollution of all kinds.
- Easy and equitable access to the materials and information needed to produce the above.
- Freedom of speech, press, religion.
- Absence of all forms of prejudice – race, religion, gender, age, sexual preference.
- Respect and celebration of the diversity of all cultures and nations.
- Strong social supports for individuals, families and communities.
- Strong social incentives that foster initiative, trust, co-operation, respect and love.
- Absence of all forms of torture, degrading treatment or punishment.
- Access to credit.
- Access to full equality before an independent and impartial tribunal.
- Access to the right to nationality.
- Access to the right to perform public service in one's own country.
- Access to rest and leisure.
- Access by mothers and children to special care and assistance.
- Access by children to special protection.
- Access to spiritual growth and fulfilment.

Figure 10 - WGI's 'Preferred State'

3.4.4 Summary

Well-being or welfare, goes beyond the basic material needs of survival. It seems that attempts to quantify the concept of welfare are difficult, but that indices such as the ISEW can at least provide a barometer of welfare by providing a more useful record of the contribution of the economy to society.

Sustainability is a state where welfare is ensured indefinitely. It is akin to happiness and is dependent on the satisfaction of material, social and spiritual needs. Sustainability – like welfare – is critically dependent on equity, which is a need for equal opportunity whether within or between generations. Inter-economic equity is in fact crucial in this respect. If third-world poverty (lack of welfare) is to be alleviated, a more equitable playing field is a prerequisite within which peoples can adopt their preferred cultures.

The definition of sustainability is further refined in sections 3.5 and 3.6 respectively by considering the availability of natural capital.

3.5 Limits to the Use of Natural Capital

The availability of natural capital is fundamental to sustainability and *physical* welfare needs. Natural capital comprises all the goods and services that support both mankind and nature (see 3.5.2 Defining Life Supporting Resources). The economy is limited at both ends of its throughput: upstream it is constrained by the quantitative availability of natural capital, and downstream by the accumulation and pollution of wastes and emissions. To be sustainable, the economy must observe these limits (see section 3.4.2 Economy and Welfare). How well the limits are observed is a direct function of consumption patterns within the system of anthropogenic processes.

3.5.1 Limits Implied by the Earth's Boundaries

There are basic finite limits to anthropogenic use of the earth's material resources dictated by its finite nature as illustrated in Figure 11 below. These limits are derived from the earth's form as a thermodynamically closed system [a closed system can exchange energy, but not mass, with its surroundings].

1. Rates of extraction of life-supporting non-renewable resources do not exceed the rate at which renewable alternatives can be found and exploited.
2. Rates of extraction of life-supporting renewable resources are maintained within the regeneration rate of the crop**.
3. Rates of discharge of wastes and emissions are such that they do not reduce the availability (both quantity and quality) of other material resources.

** The term crop is used here in the sense of any biomass that is harvested.

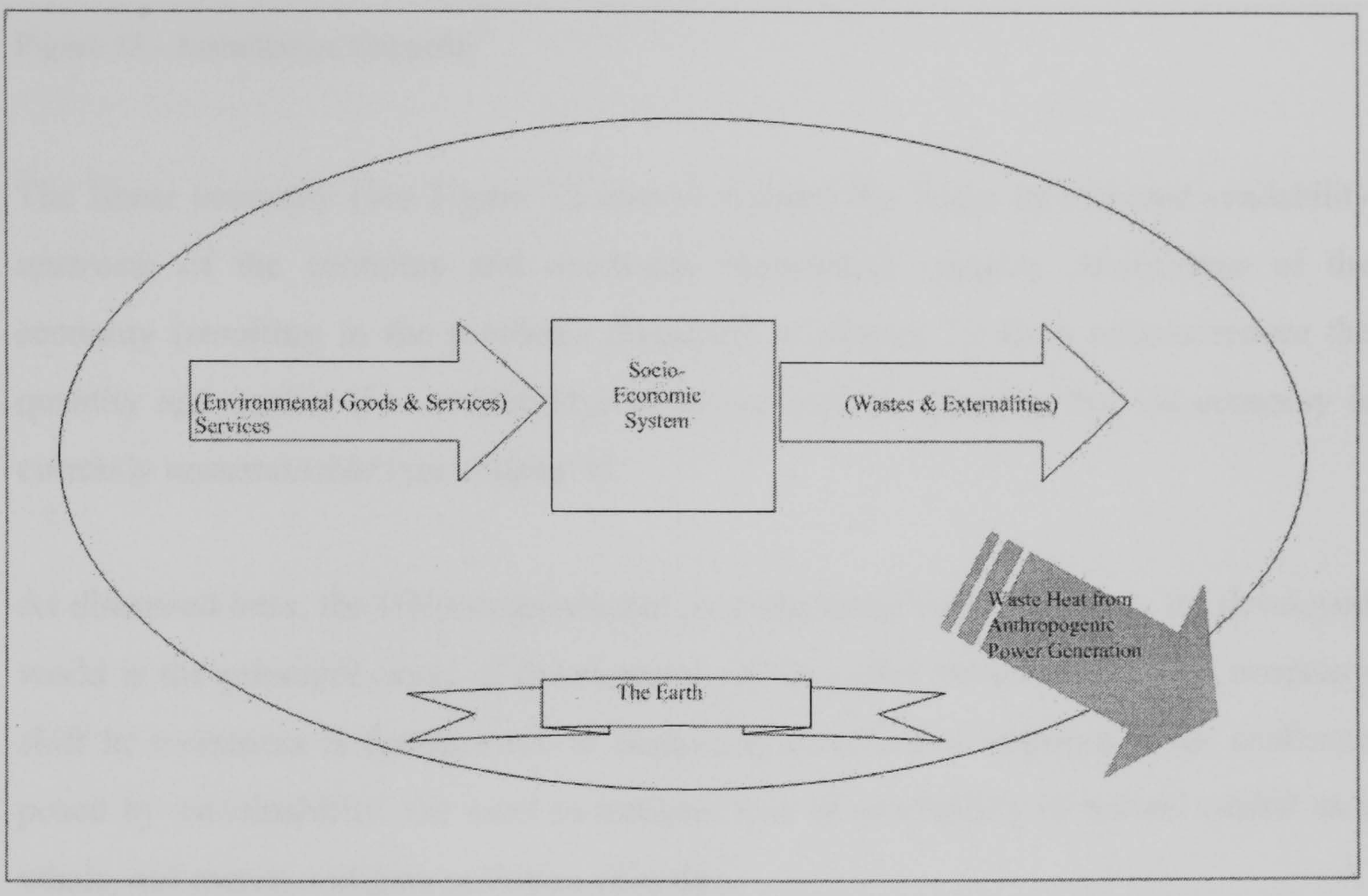
Figure 11 - Limits to Material Use Implied by the Earth's Boundaries

It is important to recognise these limits in the definition of sustainability. The limits define (in part) the carrying capacity of the earth. Carrying capacity is defined by Gilpin as [120]:

> "The maximum number of individuals of a species that can be supported in an area ... and is the maximum population that can be supported on a sustainable basis."

Carrying capacity of the earth (i.e. including humans) is more complicated than the limits described in Figure 11 for two main reasons. The first is that carrying capacity is dependent on the availability of natural capital (see 3.5.2 Defining Life Supporting Resources). The second is that anthropocentric factors such as technology [121] have an influence. Understanding resource and discharge limits is critical: **mankind must recognise there are limits to the availability of natural capital**.

Currently, the way in which we live in the developed world seems to ignore the constraints imposed by the limits described above. Most consumption of material resources occurs through a linear process – i.e. materials are removed from the natural environment, processed or manufactured into a desired product, distributed, consumed and disposed of [122]. This is essentially the 'linear economy' as described by Pearce and Turner [123] or the 'disposable society' in more colloquial terms. This maximises the depletion and destruction of natural capital. Every product that is 'consumed' is replaced with a new article often made from virgin raw materials, rather than recovered from waste. The linear economy is illustrated in Figure 12.



Note that the large arrows are intended to reflect significant linear throughput from the biosphere through the economy back to the biosphere.

Figure 12 - The Linear Economy

For the third limit in Figure 11 to be observed, the concept of 'assimilative capacity' must be introduced (see Figure 13 and discussion of assimilative capacity on page 255). Pearce and Turner discuss assimilative capacity, and rates of extraction of renewable and exhaustible resources in their model of a 'circular economy' [124].

"The capacity of natural assets such as the atmosphere, bodies of water, oceans and forests to absorb pollutants within certain limits without detrimental effects."

Source: Gilpin [125]

Figure 13 - Assimilative Capacity

The linear economy (see Figure 12 above) violates the limits of resource availability *upstream* of the economy and overloads assimilative capacity *downstream* of the economy (resulting in the problems discussed in chapter 2). Both actions reduce the quantity and quality (i.e. availability) of natural capital, meaning that the economy is currently unsustainable (see chapter 4).

As discussed later, the UN recognises that overwhelming consumption by the developed world is the principal cause of deterioration of the global environment. This necessary shift in awareness is fundamental to beginning an effective response to the challenge posed by sustainability: the need to mitigate loss of availability of natural capital as a whole, not merely mitigate pollution episodes.

3.5.2 Defining Life Supporting Resources

For sustainability to be achieved, all kinds of resources on which the economy and life itself depend have to be preserved – see Figure 14 below, Appendix A and Ekins in *Taking Nature into Account* [126]. In this thesis, the term 'resource' is employed in its widest sense[†], for example biodiversity, nutrient cycles and assimilative capacity are critical life supporting resources as well – even though these are functions, processes or otherwise not physical entities [127]. Likewise, renewable energy is a life supporting resource.

[†] The definition of environment used in ISO 14001 includes the human environment as well as the natural environment as commonly understood. This is in line with the approach taken in this thesis. ISO 14040 contradicts this to a degree by stating that LCA typically does not address the economic or social aspects of a product.

1) Land & Soil
2) Hydrosphere
3) Atmosphere
4) Nutrient cycles
5) Biodiversity
6) Renewable Resources (including biomass)
7) Non-renewable Resources (including biomass)
8) Assimilative Capacity
9) Various Services (including climate stability, humidity and temperature)

Note that Appendix A describes these groups of resources in more detail and the critical interrelationships between the groups.

Figure 14 - Life Supporting Resources

Most of the groups of resources in Figure 14 are inextricably linked to each other. Preservation of water availability, for example, requires conservation of soil and biotic resources such as trees (the converse is also true). Biodiversity likewise depends on other features of life support, while assimilative capacity is wholly dependent on the various mechanisms of healthy ecosystems. Anything that irreversibly depletes or otherwise damages these environmental goods and services will affect the availability of a given resource to support life and may consequentially be unsustainable. This kind of effect was defined earlier as a Resource Availability Infringement (see page 35).

The concept of resource availability is a critical element of the definition of sustainability being developed here. Although it is possible to make sustainable use of non-renewable resources such as fossil resources by (sustainably) exploiting renewable alternatives at the same rate, 'consumption' of biodiversity and activities that interrupt nutrient cycles reduce the *availability* of such resources and may be inherently unsustainable. The risk posed depends on what availability is lost, where and at what scale. Unfortunately we cannot be certain of any 'safe' limits in the loss of biodiversity and so on – continuing to push these limits means we are gambling with the very processes that collectively support nature itself. The Precautionary Principle is important here (see 3.6.1.2 Minimising Damage).

The consumption of some resources is unsustainable outright and simply **cannot** be substituted with a renewable alternative, hence the necessary pursuit of strong as opposed to weak sustainability (as discussed on page 35). Critical examples include biodiversity (as discussed in Appendix A) and minimum resource base critical to the survival of an ecologically significant species or population. Conversely, with careful management, it is possible to harvest biotic resources in such a way as to maximise the regeneration rate [128]. This is going beyond managing concerns about stocks to employing the natural environment to mutual gain. Some renewable resources are only renewable with careful management, for example fish stocks or the timber products of tropical rain forests.

For renewability there is an issue of *time*. Short rotation coppice may be able to provide a renewable source of biomass fuel and no less sustainably than conventionally grown tree crops *but in a much shorter timeframe*. A report to the Finnish Ministry of trade describes peat as 'slowly renewable' in discussing its use as a 'biomass fuel' [129]. This is a more liberal definition of 'renewability' since it takes upwards of 40 years – to hundreds of years – for rotting vegetation to turn into peat. Taken to an extreme however, some might term exploitation of old-growth trees in a mature habitat as 'renewable' in the sense that they might 'grow back', but the time taken could be generations and therefore outwith a reasonable definition of 'renewability'.

The availability of assimilative capacity as a resource (see Figure 13) is governed by rate considerations such as the biological oxygen demand placed on a river by some organic effluent. It is important not to exceed an environment's ability to 'assimilate' waste flows or risk damaging that environment and its natural capacity for waste processing. It is also true that assimilative capacity does not exist for all materials in all environments. Some man-made materials are not naturally neutralised at all (e.g. nuclear wastes). Thus assimilative capacity is space and time dependant. For example, just because the river in the above example may be able to absorb biological oxygen demand, it does not follow that it could tolerate metal finishing waste water for which any natural assimilative capacity is difficult to find.

It follows that beyond providing life support and other benefits to mankind, maintenance of natural capital in all its forms is critical because:

- **natural capital includes non-material services such as assimilative capacity and biodiversity; and**
- **the availability of natural capital is critical to life itself *including* the continued existence of mankind.**

3.6 Maximising the Availability of Natural Capital

It is extremely unwise to test the limits of material exploitation because of the uncertaintities involved. Instead, the Precautionary Principle must be applied (see 3.6.1.2 Minimising Damage), to accommodate margins of error. Because of the amount of destruction that has already occurred, maximising natural capital by restoring where possible, some of that which has already been lost is often more important than merely conserving what is left. This means operating as far below any limits that can be defined as possible, i.e. seeking to *maximise* natural capital. After all, it is the closest or most limiting boundary that will stop us – whatever that active constraint may be [130].

It would be difficult to calculate the limits to the use of natural capital because – as already discussed on page 46 – it is more than just human life that must be sustained and the resources are so interdependent. Given the uncertainty surrounding limits to natural capital exploitation, and adding the necessity of lasting welfare for the individual and the community, the goal must be **to maximise the availability of natural capital, not merely conserve it.** In addition once sustainability is achieved, it is vital to *maintain* it. The challenge is to design systems which not only have no adverse affects on life support but which also enhance it.

So how can the availability of natural capital be maximised? Simply reducing the stress (whether consumptive or disruptive) on the earth's resources will be a good starting point and increase the availability of resources *per se*. While reducing the load on the environment is pivotal – as discussed later – regulating the net throughput of the socio-economic system toward the absolute minimum is also indispensable. The ability to continually ensure welfare while maximising the availability of natural capital is seeking a complete win/win situation. In contrast, by not seeking sustainability, both the natural environment and welfare eventually suffer. It is evident then that global welfare is not possible without the continued availability of resources: welfare is crucially dependent on need satisfaction which can only be achieved indefinitely if the required resources are available forever. To satisfy the requirements of welfare which involves maximising this availability, the following principles are evident:

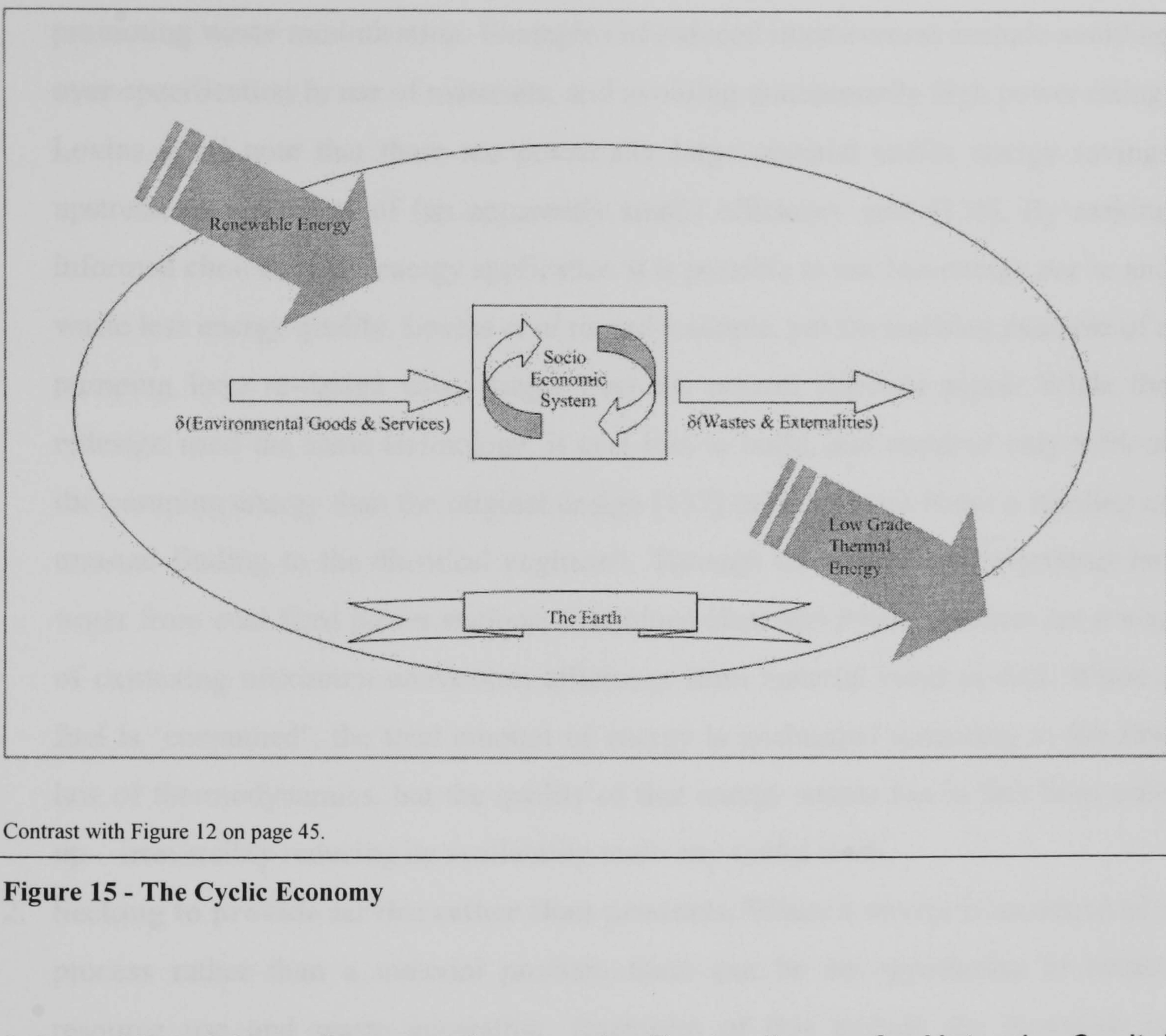
1. **To achieve welfare for future generations – key to sustainability – net levels of consumption and material throughput have first to be tempered both in quantity and quality so that resources are conserved; and**
2. **maximising natural capital is also a prerequisite for sustainability because we must restore some of what has already been degraded and employ the Precautionary Principle in not operating at limits.**

These principles, which essentially encompass the notion of strong sustainability, are embodied in Figure 15 (below) which depicts significantly reduced net throughput. Seeking to maximise the availability of those goods and services that *have been* exploited – will reduce the net throughput of the socio-economic system and inherently reduce the stress on the natural environment. This approach must be added to the definition of sustainability.

Sections 3.6.1 and 3.6.2 expand on the conservation and enhancement of natural capital. Figure 15 depicts the *cyclic* or *closed* economy. The Engineering Council describes the success of a closed economy in terms of [131]:

> "how little energy and raw materials are consumed [and] how much can be retained within the economy".

It is useful to compare this diagram with Figure 12 which represents the current world model. Note that while this model is reliant on a constant stream of material resources (including fossil resources for power generation), the preferred model only requires a net flow to 'top up' the materials dissipated from the socio-economic system. This economy would be characterised by 'clean technology' [132] and renewable energy sources in the long term (renewable energy is further discussed on page 62). Note that the thin arrows in Figure 15 below reflect a significantly lower load on the environment than the linear economy (Figure 12 on page 45) and account for entropic losses which will inevitably occur.



Contrast with Figure 12 on page 45.

Figure 15 - The Cyclic Economy

3.6.1 Minimising Consumption and Destruction of Natural Capital (Conservation)

Starting from the present situation there are two key ways in which to minimise the consumption and destruction of life supporting natural resources. The first is through seeking efficiency and the second is through minimising damage *per se*.

3.6.1.1 Efficiency in Material and Energy Use

There are several strategies for seeking material and energy efficiency:

1. **Seeking material and energy efficiency *per se*.** This is often referred to as 'dematerialisation' [133]. This may be found reflected in the growing policy

adoption of the goal of a four or ten-fold increase in efficiency [134] – also known as 'Factor 4' or 'Factor 10' Economies. Lovins, Lovins and Hawken, major proponents of material and energy efficiency, record that the US economy is only 10% as energy efficient as the laws of physics will allow; and considerably less materially efficient [135]. Seeking material and energy efficiency is an fundamental way to improve sustainability, directly reducing extraction of natural resources and promoting waste minimisation. Examples of reduced intensiveness include avoiding over-specification in use of materials, and avoiding unnecessarily high power rating. Lovins *et al* note that there are potentially large material and/or energy savings upstream of the point of (an apparently small) efficiency gain [136]. By making informed choices about energy application it is possible to use less energy *per se* and waste less energy quality. Lovins *et al* record a simple, yet far-reaching example of a pumping loop re-design using larger than the normal diameter pipes. While the redesign used the same technology, it cost less to build, and required only 92% of the pumping energy than the original design [137] (although this is not a startling or unusual finding to the chemical engineer). Through the use of the by-product hot water from coal fired power stations, Combined Heat and Power schemes are a way of extracting maximum conversion efficiency from material burnt as fuel. When a fuel is 'consumed', the total amount of energy is unchanged according to the first law of thermodynamics, but the quality of that energy source has in fact been used up – irreversibly reducing its availability to do any useful work.

2. **Seeking to provide service rather than products.** Where a service is an output of a process rather than a material product, there can be an opportunity to reduce resource use and waste generation. Examples of this include the provision of transport rather than cars, and information in ways that render the printed word unnecessary. Clift provides further examples including the shifting from pesticide sales to crop management services and the leasing rather than sale of products, where the owner is responsible for any waste and for product reprocessing [138]. Lovins *et al* cite a company called 'Interface' that has managed to achieve a 35-fold reduction in the flow of materials required to deliver quality floor covering through a combination of technical innovation and service-based lease scheme [139]. 'Workflow & Imaging' and 'Straight through Processing' are examples of paperless end-to-end information processing transforming the banking and finance industry, with great benefits both in terms of cost and paper/logistics. Holiday business

Eurocamp lease tents and amenities on location in Europe, negating the need for the ownership of a tent and accessories that would be relatively rarely used [140].

3. **Appropriate application.** In order to avoid potential waste of resource quality, the suitability of a given product or process for a particular application has to be examined. Examples include using unfiltered rain or grey water instead of drinking water for toilet cisterns, and using a substitute for mains electricity for space heating‡. The use of timber in constructing homes and offices is a good application since the material is renewable and its thermal efficiency can have significant advantages over other materials during the life of the building. The timber can also be reused, recycled into particleboard or burned for energy at the end of the building's life.
4. **Quality not quantity.** There is plenty of scope for the application of this strategy. Using reusable rather than disposable products can have significant gains. Products of good quality and 'built to last' can give competitive advantage over less well finished products and again can reduce the need for natural resource extraction and minimise waste. Examples are refillable pens, quality clothing, and buildings designed for comfort and to take account of wear and tear. Note that design for premature failure or 'planned obsolescence' is an unsustainable business model (see Figure 16 - Planned Obsolescence) although there can be problems in *excessive* durability.
5. **Use Locally.** Until the transition to sustainable energy sources is made, the transport of materials across long distances is one of the primary unsustainabilities of any given life cycle – using local sources reduces impacts of noise, poor air quality, and accidents [141]. Products consumed near to the point of manufacture usually have much less negative externalities than those transported across regions or continents. In terms of organic materials, consumption far removed from source exacerbates the problem of broken nutrient cycles.

‡ Electricity is a highly available concentrated form of energy that can be used for a wide variety of applications. Space heating only requires low grade thermal energy: thus if combustion must be used for space heating, it is better done on site for improved efficiency. District heating schemes (common in Europe) supply both electricity and hot water from power stations, thus significantly increasing efficient use.

Planned obsolescence is a well established technique employed by manufacturers to increase sales and has been carried out since the 1930s [142]. A question posed by Beder is [143]

"Should engineers be aiming to design more durable commodities?"

The short answer for sustainability is yes. The longer answer is that products should be appropriately durable: there is no point having a product that will long outlive its useful life if no remanufacture/recycling process exists. The economic theory of such policies is complex [144] – and doubtless its students esteemed – but 'planned obsolescence' as a mechanism to increase sales can only increase mankind's demands of the natural environment.

Figure 16 - Planned Obsolescence

3.6.1.2 Minimising Damage

There are several strategies for minimising damage to natural capital:

1. **Product Stewardship** – Product Stewardship, or *extended producer responsibility* [EPR], is where companies assume a degree of responsibility for its products beyond the factory gate, employing life cycle awareness to the company's product(s). Examples are designing more easily recycled products, product take-back schemes, product refurbishment services, and packaging waste recovery schemes. A significant promoter of product stewardship is Hewlett-Packard, pioneering material recovery from obsolete technology [145]. German law already makes many manufacturers forever responsible for their goods [146], and in the UK Defra (Department for Environment Food and Rural Affairs) has brought in take-back legislation for companies in the packaging producer and user chain [147]. Note that EPR requires producers to take a degree of responsibility not just for end-of-life products, but also [148]:

"for their upstream activities inherent in the selection of materials and in the design of products".

2. **Seek zero emissions.** Some might argue that the concept of 'zero emissions' or 'zero waste' is unobtainable in an industrial society, or downright technically impossible from the perspective of thermodynamics. But, while thermodynamically impossible [149], approaching the ideal goal of zero waste through industrial ecology, mankind can make significant steps towards *zero pollution.* The goal of total quality in manufacturing was considered absurd yet this did not stop many Japanese manufacturers achieving excellence through the pursuit of perfection [150]. The quality revolution only became possible when total quality was defined as the overriding goal [151].
3. **Apply risk assessment and the principle of precautionary action.** Risk assessment is often used to manage the threat of harm, but there is growing concern that risk assessment can deliver ambiguous results [152]. The Precautionary Principle must be adopted, such as was defined in the Rio Declaration [153] (Figure 17) and by the Wingspread Statement [154] (Figure 18). Note that the principle does not *preclude* any action, but does oblige the analyst to consider the alternatives, including the alternative of 'doing nothing'. In the absence of data on which to base a risk assessment, it is imprudent to proceed without considering these alternatives.

"In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

The Rio Declaration on Environment and Development, 13 June 1992.

Figure 17 - Rio Declaration Definition of The Precautionary Principle

The Wingspread statement followed a two-day workshop to define the Precautionary Principle. Montague summarises the Precautionary Principle as follows: -

1. People have a duty to take anticipatory action to prevent harm.
2. The burden of proof of harmlessness of a new technology, process, activity, or chemical lies with the proponents, not with the general public.
3. Before using a new technology, process, or activity, people have an obligation to examine "a full range of alternatives" including the alternative of doing nothing.
4. Decisions applying the Precautionary Principle must be "open, informed, and democratic" and "must include affected parties".

Montague, February 1998 [155].

Figure 18 - The Wingspread Statement on the Precautionary Principle

3.6.2 Maximising the Availability of Materials within the Socio-economic System (Enhancement)

This section is split into two parts: the first is a discussion of 'industrial ecology' and discusses in general terms the means of maximising the availability of materials within the socio-economic system. The second part is about more explicit strategies for maximising the availability of resources within in the socio-economic system.

3.6.2.1 Industrial Ecology

A useful approach to maximising the availability of materials within the socio-economic system is to mimic the example set by nature itself. There is little 'waste' in nature from the perspective that material is continually made available again to different species through natural cycles. Natural systems are efficient in their use of material and energy, appearing to operate outwith the second law of thermodynamics by using sunlight to concentrate dispersed highly entropic (Figure 19) matter into organised material in the form of biomass. An essential difference between mankind and nature is that mankind largely uses materials to generate power rather than depending on solar energy exclusively, thus dissipating the material resources irreversibly and losing its availability.

Entropy is the 'unavailability of a system's thermal energy for conversion into mechanical work'. It can also represent the 'degree of disorder or randomness of the constituents of any physical system'. From The Oxford English Reference Dictionary[156]

Figure 19 - Entropy

Nattrass and Altomare note that [157]:

> "The net increase in material *quality* on earth is produced by sun-driven processes. Photosynthesis is the only large-scale producer of material quality."

Of course, nature doesn't actually cheat on thermodynamic law, as Nattrass and Altomare point out [158]:

> "While the Earth is a closed system with regard to matter, it is an open system with respect to energy. This is the reason why the system hasn't already run down with all of its resources being converted to waste."

Emulating nature's processes is often referred to as 'industrial ecology' [159]. Lowe defines industrial ecology [160]:

> "The heart of industrial ecology is a simple recognition that manufacturing and service system are in fact natural systems, intimately connected to their local and regional ecosystems and the global biosphere ... the ultimate goal of industrial ecology is bringing the industrial system as close as possible to being a closed-loop system, with near complete recycling of all materials."

Natural processes differ from anthropogenic processes principally because they are typically cyclic and operate within the solar energy pathway (either directly or indirectly). In contrast, anthropogenic processes are linear and often make materials unavailable for reuse. They operate largely outwith the solar energy pathway, i.e. they rely on fossil 'fuels'. These differences are summed up in Figure 20.

Natural Processes:

- Coexist in an interacting web
- Operate in cycles and continually make materials re-available
- Operate within the solar energy (high availability) pathway
- Natural processes are naturally sustainable
- *Natural processes are self-perpetuating*

Current Anthropogenic Processes:

- Are largely individual
- Are linear and continually make materials unavailable (esp. non-renewables)
- Operate largely outwith the solar energy (high availability) pathway
- Many anthropogenic processes are inherently unsustainable
- *They cannot go on for ever***

** Anthropogenic use of renewables is potentially sustainable. Constraints to renewability are discussed later.

Figure 20 - Natural and Anthropogenic Processes – a Comparison

In order to become sustainable, mankind and its socio-economies would benefit from emulating some of nature's characteristic processes. A move away from the disposable society to cyclic systems would make material readily available – i.e. both in terms of quantity and quality – for re-use within the socio-economic system. The consequential reduction of the waste load on the environment could also aid assimilation by nature when material is finally returned to the natural environment. An example is the increasing manufacture and use of composted domestic organic wastes by local authorities.

A continual process to keep materials available within the socio-economic system will necessarily require an ongoing, and sustainable, energy input. Sustainable power generation is discussed below.

3.6.2.2 Strategies to Maximise the Utility of Materials in the Socio-economic System

Section 3.6.2.1 discusses maximising the availability of resources in the socio-economic system from the point of view of industrial ecology. This concept is useful as it helps to set the context for the strategies presented below. By extracting maximum utility from materials in the socio-economic system it is possible to maximise the benefit gained from environmental goods and services while minimising what is extracted from the natural environment and the wastes that have to be put back. Key strategies include:

1. **Implement Sustainable Power Generation**. Implementation of renewable energy is fundamental to the ability to close up material cycles and maintain materials within the socio-economic system (see Figure 21) as this will usually require a sustained energy input.
2. **Reuse.** This means product reuse for its originally intended purpose as opposed to material recycling (discussed below). The classic example is the returnable milk bottle. Many building materials are increasingly reused e.g. bricks, slate and timber.
3. **Remanufacturing/Reconditioning**. Remanufacture is the re-processing or reconditioning of a product such that it is fit once again for the original purpose. Remanufacturing of goods can significantly reduce anthropogenic throughput of a given commodity and potentially has the benefit of being less energy intensive than material recovery (see recycling below). Design for maintenance, serviceability and disassembly are similar product traits. Examples include vehicle engines and white goods.
4. **Recycling**. Recycling is important in maximising material retention in the socio-economic system and extracting maximum utility from it (but this is not universally true – see below). Because of the large waste of energy that is sometimes involved in primary production, it is important that highly available materials (e.g. pure metals) are not squandered. Recycling materials to successively less demanding applications ('down-cycling') is a method of prolonging the useful life of raw materials. Composting of perishables is another form of materials recycling and is important for nutrient management. Note that recycling does not universally present the best option for either keeping material within the socio-economic system or for the wider strategy of maximising the availability of natural capital. Depending upon the specific context, it may be for example more appropriate to recover energy from a given 'waste' stream than recover the material [161].This may be particularly true in

the case of paper. Paper can be recycled several times before the fibre becomes unusable. However, the resources consumed in the process of collecting and de-inking can be high, particularly as waste paper is often traded over long international routes. Incineration may prove to be the better option: the optimum (or ratio) would depend on specific circumstances.

Making the transition to renewable energy and closing material loops are presented as core strategies for sustainability. The need to make the transition to renewable energy sources is so fundamental that the requirement should be added to the definition of sustainability. It may be that the act of recycling increases local air emissions (for example) but this is where life cycle context comes into its own in identifying potential impacts that can be managed.

The United Nations Development Programme's year 2000 report on Energy and the challenge of sustainability noted that [162]:

> "Realising sustainable futures will require much greater reliance on some combination of higher energy efficiencies, renewable resources, and advanced energy technologies."

Energy must be used in order to maintain the availability of materials within the socio-economic system, so there may be increased energy usage in order to maintain material availability through remanufacturing, reprocessing, recycling, recovery processes required in a cyclic sustainable economy. Efficiency gains can be made through combined heat and power technology, innovation in electrical appliances and so on. Efficiency gains based on unsustainable energy lessen the problems of the transition to long term sustainably-produced energy, but they are clearly not the long term option, hence the UNDP's call for renewable energy.

Nature continually makes materials available for re-use in cycles ultimately powered by solar energy. But mankind has learned to exploit other forms of renewable or 'clean' energy: it is possible to harness wood, wind, solar, wave and hydropower which all result from solar energy. There is potential to make increased use of other forms of energy such as tidal power and geothermal power. Through controlled combustion it is also possible to generate power from specifically grown plant fibres – such as short rotation coppice [163] – while ensuring that there is sustainable replacement of the harvested materials. Renewable energy is further discussed later (see 4.2.2.2 Energy).

It is important to take a critical view of the whole system when assessing the sustainability of energy production and use. What solution may present itself as the best in general may not be the best technology/process in specific situations – just as material recycling is not the all round panacea to environmental ill (as is often popularly held to be).

Figure 21 - Transition to Sustainable Power Generation

3.7 Towards an Operational Definition of Sustainability

3.7.1 Other Implications of Sustainability

This chapter has examined conditions for sustainability including temporal and spatial elements implicit in its definition. Elements and implications of sustainability also important to an 'operational' definition include:

- **Urgency**. It is apparent that future generations will be affected by many of the environmental and social changes being witnessed today. Conferences such as Rio, Helsinki, Johannesburg and Kyoto have led to a wider understanding of the meaning of sustainability and awareness that rates of anthropogenic change represents a significant risk. **There is an imperative for urgent action toward sustainability** if it is to mean anything in terms of commitment to the interests of the next few generations. By operating beyond the earth's carrying capacity and experimenting with the earth's life supporting systems we are truly biting the hand that feeds us.
- **Context.** Priorities and issues in working toward sustainability are likely to change depending on the temporal or spatial view taken. An immediate concern in the context of one space-time boundary may be access to safe drinking water (welfare); a medium term view loss of biodiversity (natural capital); and in the long term global climate change (welfare and natural capital). For example, an individual very low on Maslow's scale of need (i.e. survival needs) is likely to be more concerned with their immediate survival than with the wider issues of sustainability. In this person's space-time reality, sustainability simply is not important. A striking spatial dimension of sustainability is that it does cover environmental and welfare concerns from the local to global scales. This means that the context of a given process or resource is important to questions of sustainability: a tree may for example be viewed as both a (public) carbon sink or as timber for a house (private act of consumption). The 'Tragedy of the Commons' [164] – where more people have access to a resource than can be supported combined with a lack of governance – can mean that 'renewable' doesn't equate 'sustainable'. Furthermore, sustainability cannot be reached through sustainable use of a specific resource: simultaneous and sustainable use of all resources is a precondition for sustainability [165]. [Clearly, individual activities will be deemed 'sustainable' if they have the potential to go on *ad infinitum*.]
- **Transition Period**. Clearly sustainability cannot be reached 'overnight', even though there is a need for urgent action (as illustrated above). While much can be done immediately in terms of improved efficiency for example, some

infrastructure cannot be changed quickly; business must learn to adapt; governments need to employ different accounting practices and so on.

3.7.2 Proposed Definition

This chapter has explored the conditions for and implications of sustainability. The definition of sustainability, its properties and strategies for achieving it are summarised below.

Sustainability is a state which ensures the satisfaction of needs and welfare of those alive today and generations to come. At the same time, all resources (physical or intangible) required to support life and meet needs have to be continually available and in many cases replenished. In the state of sustainability, all economic practice rewards behaviour that supports welfare and maximal availability of resources.

It is apparent that many critical resources are in decline largely due to the unsustainable nature of life-styles enjoyed in the developed world. Loss of availability of some natural resources is reaching a crisis scale. The degree of 'linear' material throughput in the world economy is prohibitive and is of a size and nature incompatible with environmental capabilities. Thus in order to *reach* the state of sustainability, the underlying life giving resources have to be maintained and in many cases replenished. Anthropogenic processes underpinning the economy and our lifestyle have to be operated in a way that respects and avoids infringing social and natural environment limits. Several key observations and requirements have emerged from the analysis carried out in this chapter:

- The state of sustainability requires the adoption of 'strong sustainability', i.e. resources are not usually capable of substitution.
- All manner of equity are a prerequisite for sustainability including trans-national, inter-generational, and economic.
- The achievement and maintenance of welfare is dependent on the continued availability, i.e. quantity and quality, of all social and environmental resources. These include the whole range of environmental goods and services – including biodiversity and assimilative capacity – required for life support and for

processing into goods and services for the satisfaction of needs. It is important to reduce the net load on the natural environment by operating closed, cyclic systems as far as possible.

- The economy is wholly dependent on environmental and social resources for its existence. Economic practice must therefore reward behaviour that supports maximal availability of these resources
- Critical resources have to be preserved and in many cases replenished for sustainability to be possible because we begin – globally speaking – from a position of environmental and social impoverishment.

Finally, *sustainable development* – defined on page 29 – is a means of contributing to the goal and state of sustainability through the provision of goods and services that meet needs; and achieved so in a manner that preserves availability of natural capital. It is important to note that a *local* goal of sustainable development is essentially an 'ideal' one since it is impossible to say that any one system is wholly sustainable until global sustainability is true. For example, if one company is using a scarce resource sustainably, but then another starts using that same resource, it may be that henceforth *both* companies are using the resource *unsustainably*. This apparent conundrum does not weaken the usefulness of aiming for a sustainable development however (see analogous discussion of zero emissions and the quality movement on page 55).

3.8 Conclusions

A definition of sustainability has been developed and presented. This has been coupled with statements that qualify the definition and minimise ambiguity. It has been shown that achieving sustainability requires going much further than simply mitigating pollution and other environmental harm. It is necessary to seek to maximise the availability of natural capital – the resources that support life on earth. Without such a strategy, there is a failure to ensure sustained welfare for the individual and the global community both now and tomorrow.

In order to maximise the availability of natural capital, the quest has to be augmented by an effort to:

1. seek to minimise consumption and deterioration of natural capital by all means possible and where possible to increase it; and
2. to seek to maximise the utility of those materials that are imported to the socio-economic system.

The latter principle illustrates the imperative of gaining the maximum benefit from a given raw material before discharging it to the environment, as well as marrying all aspects of processing with environmental and social constraints. Such strategies are far removed from the 'disposable society' or 'linear economy' that forms the current socio-economic models within the developed world. Without urgently embracing the challenge of sustainability and adopting these principles however, mankind is simply moving further and further away from a sustainable existence.

Chapter 2 demonstrated the ways in which mankind should be concerned about management – or perhaps mismanagement – of the natural environment. Chapter 3 has sought a more constructive response to sub research question (a) by presenting sustainability as a goal for environmental management effort and benchmark with which to gauge progress. Chapter 4 will conclude the response to sub research question (a) by assessing the scale of the challenge of sustainability and consolidating knowledge gained in chapter 3. Chapter 4 will also provide the framework within which sub research question (b) may be approached in Part II.

Chapter 4 – The Scale of the Challenge

4. Objectives

By consolidating knowledge gained in chapter 3, chapter 4 concludes the response to sub research question (a) by assessing the scale of the challenge of sustainability. It goes on to interpret the goal of sustainability in terms of an operational goal for environmental management tools.

4.1 Introduction

Thus far in Part I, the nature of the environmental crisis has been considered, the concept of sustainability has been introduced and a qualified definition of sustainability developed. Certain strategic actions necessary for the achievement of the state of sustainability have been presented, consistent with the goal definition.

From a practical viewpoint it is easier to identify the features of activities that are definitely unsustainable and should be avoided. Indeed, it may be said that it is 'unsustainability' that manifests itself in pollution episodes and environmental degradation. In this sense we ought to rid ourselves of unsustainable processes and thinking in order to become sustainable. In response to sub research question (a), an assessment of current unsustainable features of the modern world is made from the perspectives of natural capital (section 4.2), welfare (section 4.3.1) and economics (section 4.3.2). The chapter closes with a brief assessment of the role of stakeholders and environmental management tools (including LCA) in promoting sustainability. This assessment will include the requirements of an 'operational' definition of sustainability for such tools.

4.2 Deterioration of Natural Capital

4.2.1 Consumption: Exceeding the Earth's Carrying Capacity

Until recently, the material demands of the developed world seemed to ignore any knowledge of the existence of limits to the availability of natural resources (as discussed in chapter 3) while in many developing countries there is already a humanitarian crisis associated with resource depletion (see 4.3.1 Welfare). That the developed countries have outgrown their own carrying capacity is illustrated by the fact that they are heavy importers of many basic resources. Indeed, the relentless materialism of the developed countries and the continuing drive for economic growth (built on unsustainable processes) hold the key role in the increasingly perilous global situation. What is more the flow of such resources from the developing to the developed world – and the associated liquidation of natural capital – is inextricably linked to the creation of the 'underdeveloped' third world in the first place [166].

The UN declared in Agenda 21 that:

"The major cause of the continued deterioration of the global environment is the unsustainable pattern of consumption and production, particularly in industrialised countries." [167]

Wackernagel and Rees discuss UN figures that show that **80% of the world's resources are being consumed by 20% of the world's population** [168] (i.e. predominantly by the developed world). Moreover, Wackernagel and Rees argue that mankind has already exceeded the limits of indefinite carrying capacity [169], stating that:

"The greatest contribution the developed world can make to sustainability is to reduce its resource consumption by all means at its disposal." [170]

Evidence that the limits of the world's carrying capacity have been exceeded is encapsulated in World Watch Institute statistics (as was presented in section 2.3). It may be tempting to some to assume that loss of some plants, insects, birds, wild mammals or freshwater fish is not of importance, if these organisms are not 'harvested'. However, as part of the global system, humankind may rely on their diversity and function within the system for its survival. As Brown *et al* state [171]:

> "as various life forms disappear, they affect the entire ecosystem and particularly the basic services provided by nature, such as pollination,

seed dispersal, insect control and nutrient cycling. This loss of species is weakening the web of life, and if it continues, it could tear huge gaps in its fabric, leading to irreversible changes in the Earth's ecosystem."

This is a stark warning. It is imprudent to tamper with key components and services in ecosystems, and furthermore we may indeed be 'overshooting' the carrying capacity of the planet.

4.2.2 The Impact of Infrastructure

Generic use of the natural resources that meet the food, energy and transport demands of a 'developed world' society are discussed below. The discussion illustrates unsustainability in the infrastructure that the demands of the modern lifestyle creates.

4.2.2.1 Food Production

Agriculture is heavily dependant on soil conditions, on climate - including light and water availability - and on the external supply of nutrients. Since the industrial revolution, fishing and agricultural practice has become exploitative in its attempt to harvest as much as it can from a given area. The linear flow of materials through the process of agricultural production is a primary cause of the associated environmental problems.

Failure to return nutrients to soils through inter-cropping[§], or through the application of natural organic manures and compost, leaves soils exhausted of minerals and organic matter. This causes damage to the soil structure, nutrient availability, and leads to erosion. The demand for man-made fertilisers to replenish nutrient loss causes further disruption to natural nutrient cycles and balances. Implications of intensive agricultural practice include:

- depletion of non-renewable resources used in inorganic fertiliser manufacture;

[§] Before the advent of man-made fertilisers, farmers would rotate crops year-on-year, to avoid depleting the soil of nutrient. Inter-cropping with leguminous plants such as clover or alfalfa was often practised, i.e. plants that naturally 'fix' Nitrogen from the air via root nodules that contain nitrogen-fixing bacteria.

- eutrophication of surface and coastal waters (reducing water availability and damaging aquatic water systems);
- the potential need to remove nitrogen compounds from drinking water; and
- 'slurry lakes' created by livestock: a resource turned into waste, and a potential pollutant.

Many of these observations also apply to stock, poultry and dairy farming as these forms of farming also use biomass, such as grass and grain, as feed-stocks. Another significant feature of intensive agricultural practice is the use of monoculture, i.e. growing only one crop in one large area of land. Done mainly to facilitate throughput, problems include:

- loss of biodiversity;
- loss of habitat;
- increased potential for plague;
- an artificially created 'need' for pesticides/insecticides, despite the known dangers including the loss of insects necessary for pollination and a fundamental part of many food chains;
- a created 'need' for pesticide resistant crops, e.g. genetically modified crops; and
- a loss of a varied, local source of food.

In spite of the above, organic and permaculture based practices have been around for some time now, and the demand for organically grown food is growing at least among some parts of society.

4.2.2.2 Energy

Nature gains its energy directly or indirectly from solar energy, and yet humankind has become dependent on fossil resources. This dependency is short-sighted: irrespective of whether the active constraint will turn out to be smog, scarcity, carbon dioxide poisoning or enhanced greenhouse effect, all such problems lead to the undermining of resources and to unsustainability. Alternative means of generating power exist which are more efficient or at least wholly based on cleaner, renewable sources.

Combustion of fossil resources is a major reason for damage to natural capital. Such combustion is known to be responsible for failures to maintain natural atmospheric conditions, with consequences such as NO_x/SO_x production, airborne particulate, smog and acidification. These phenomena can also lead to other pollution episodes such as acidification of watercourses; bound-metals leaching from soils; and damage to plants and human health. Despite these arguments in favour of adopting alternative energy sources, mankind continues to grow more reliant on highly unsustainable use of valuable fossil resources**. The Worldwatch Institute estimates that 1996 world-wide consumption of fossil resources was 8.1 billion tonnes of oil equivalent, which [172]:

> "provided roughly 85 percent of the world's commercial energy."

This fossil resource consumption figure is the highest yet recorded by the institute.

Nuclear power as an alternative to the combustion of fossil resources has long been a controversial issue because of the risks involved in nuclear fission and resulting wastes. The net electricity generating capacity of the world's nuclear power plants recorded by the Worldwatch Institute for 1996 was 344 gigawatts – over 25 times that of generated capacity of solar, wind and geothermal energy combined. But current nuclear power technology has no hope of being sustainable as there is no such thing as assimilative capacity for nuclear waste. By definition, the hazard associated with a material is its intrinsic ability to cause adverse effects. Since nuclear waste is highly detrimental to any living organisms with which it comes into contact - this makes nuclear waste extremely hazardous. Worse still, radioactive waste has the potential to cause extreme resource availability depletion through contamination and remains dangerously unstable for thousands of years to come.

Risk is usually measured in terms of an equation, for example [173]:

Risk = (severity of consequence) x (probability of occurrence)

** In contrast, the use of these resources as raw materials for potentially recyclable materials, such as plastics, utilises the resources in a manner that can provide benefits over a much longer period of time than does combustion. Furthermore, while its possible to make plastics out of 'fossil fuels' it would be difficult to manufacture plastics from wind power!

Thus, the only option for 'disposal' of nuclear waste (that which is not re-processable) is not to 'dispose' of it at all: it is normally stored on-site at nuclear facilities awaiting shipment to a geological 'repository' [174]. Long-term sealing of the waste leaves the hazardous material preserved for many thousands of years and the assumption is made that the location chosen is seismically or otherwise 'safe'. Clearly those that are taking the decisions about these matters are unlikely to be held to account in decades or millennia to come if it turns out that the location of a given repository is not safe. Yet, this is precisely what might happen at the proposed Yucca Mountain repository, Nevada, US [175]:

> "[nuclear] reactors where the waste is now stored are licensed by the NRC and are on solid, stable ground with negligible earthquake activity. By contrast, the area where its proposed to ship the waste is among the most seismically active in the country and would not meet the same NRC licensing standards for reactors. Since site characterization studies for the Yucca Mountain dump began, there have been dozens of earthquakes, including a magnitude 5.2 quake in 1992 which caused over a million dollars in damage to government buildings at the Yucca Mountain site. There have been 621 seismic events of a 2.5 magnitude or greater in the last 20 years."

Waste material which on direct contact could immediately deliver a potentially fatal dose, and which poses such an extreme management problem, is wholly unsustainable. While it is too late to avoid the generation of the waste that already exists, and indeed to avoid the generation of further nuclear waste with nuclear power being part of the current energy infrastructure, it is never too late to question the long term viability of the process as it currently stands. A similar view is expressed by the Royal Commission on Environmental Pollution (RCEP) [176]:

> "New nuclear power stations should not be built until the problem of managing nuclear waste has been solved to the satisfaction both of the scientific community and the general public."

[It is interesting to note the recognition by the RCEP in the latter quote of the importance of an aspect of social sustainability].

There is also debate over whether renewable energy is an all-encompassing panacea to problems of present-day energy infrastructure. Trainer argues that a massive reduction of overall energy consumption is necessary to move completely away from unsustainable fossil and nuclear energy resources, because renewables cannot provide power in the sorts of quality and quantity that rich countries currently take for granted [177]. Blunden and Reddish discuss research that suggests that the UK could potentially generate the majority of its electricity demand (at 1992 levels) from renewables [178]. But this assessment does not cover alternatives for powering current transport infrastructure: the energy used in transportation – predominantly petroleum – amounts to over a third of total UK energy demand [179] (see Figure 22 for 2001 figures). A huge amount of energy and fuel is wasted through inefficient transmission and motive technologies.

On meeting the UK's energy requirements with renewables, Jackson and Löfstedt, report that [180]:

> "Direct insolation rates in the UK are lower than in many other European nations. Even so, direct solar conversion technologies could supply enough electricity to meet present levels of demand using less than 3% of the UK's land area. The accessible wind resource alone could generate twice the current level of electricity demand. Biomass – mainly from energy crops – could supply more than 75% of the UK's demand for electricity, or contribute substantially to the demand for transport fuels."

Clearly, Jackson and Löfstedt are not advocating covering 3% of the UK land area with photovoltaic panels, nor re-planting all agricultural land with energy crops. However, their words convey an important message, namely that the combination of available renewable, clean technologies *with concerted energy conservation effort* means that the UK can meets its energy requirements without relying so heavily on fossil or nuclear energy sources. That is not to say that renewable power isn't without its problems: few if any technologies have **no** environmental impact; the wide range and flexibility of renewable energy technologies can weaken their potential as a serious competitor with current technology; and there are problems associated with power generation based on unpredictable weather. The RCEP sum up in their 28th report [181]:

> "There is great potential for the UK to obtain energy from renewable energy sources. Realising that potential will be dependent on adequate government support, careful attention to their particular characteristics and public acceptance for the necessary installations."

	Industry	Domestic	Transport	Services	Total
mtoe	**35.2**	**48.6**	**54.9**	**22.1**	**160.8**
percentage	**22%**	**30%**	**34%**	**14%**	**100%**

[mtoe: million (10^6) tonnes of oil equivalent]

Source: UK Department of Trade and Industry [182]

Figure 22 - UK Energy Demand by Sector (2001)

4.2.2.3 Transport

Modern life in the developed world is heavily dependent upon transport, not least because transport is relied upon to deliver raw materials, food and other basic needs. Transport is also employed to get to places of work, to do business and to visit friends and family. Like agriculture and energy (considered above) almost all motorised transport is inherently unsustainable as it is currently dependent on fossil resources as a source of fuel. The Worldwatch Institute report that world-wide increase in the use of motor vehicles is responsible for the highest ever demand for oil [183]. As with energy, the problem is twofold: the act of consumption itself **and** the resulting potential for environmental harm including acidification and smog.

Lovins *et al*, major proponents of material and energy efficiency, record that as little as 1% of the energy consumed by the average automobile is used to transport the driver

[184]. This incredible lack of energy efficiency is reflected in the fact that the energy requirement for transport in the UK is larger than that consumed by the domestic sector or that of industry (Figure 22). The process of automobile manufacture similarly involves staggering amounts of material resources (Figure 23).

The use of the car, long a symbol of status and affluence represents an alarming problem from the perspective of sustainability: in the forty years it is taken for the world's population to double in size, the number of cars has increased nearly tenfold [185]. Car production now consumes more resources than any other industry including 20% of the world's steel production, 10% of aluminium, 35% zinc, 50% lead and 60% of all natural rubber [186].

Figure 23 - Resources involved in Car Production

Another major unsustainable feature of current transport infrastructure, affecting welfare, is the huge loss of life and injury caused on the roads: in Britain in 1993, road accidents were responsible for 3,820 deaths, 1,250 serious injuries and over 250,000 casualties [187]. Concerned about the rising death tolls of car accidents, traffic jams and pollution, car travel has become a major concern of the UK government who plan increased use of public transport [188]. As Cairns points out, the UK government is targeting car use only, not ownership, as the latter would be 'politically and economically suicidal' [189]. This would however be a significant step towards a more sustainable transport infrastructure if the new policies prove successful.

4.3 Socio-economic System

4.3.1 Welfare

Current inequalities in global distribution of material resources reflect the distribution of financial wealth. Reid discusses UNDP figures reporting that the richest 20 percent of the world's population appropriate 82.7 percent of the total world income, while the world's poorest 20 percent receives a mere 1.4 percent [190]. Reid further observes that the extreme poverty suffered by the poorest 20 percent of the population (over a billion people) is associated with malnutrition, a lack of safe drinking water, sanitation, health care and housing. Yet these statistics do not address the obvious and extreme differences in wealth *within* a given nation.

Welford and Gouldson note that addressing this inequity is a key issue for sustainability [191]:

> "The massive inequality that exists in wealth and standards of living displayed across the world make sustainable development [hard] to achieve. Those living in the Third World often aspire to the standards of living of the First World and we know from an environmental stance such aspirations are presently not achievable...environmental improvement is inextricably linked to wider issues of global concern which do need to be addressed."

It is no coincidence that the developed world appropriates the lion's share of available resources and that the developing world still suffers. The situation suffered by these countries has ultimately been caused by the developed countries, i.e. Europe, North America and the former white colonies [192]. Yet it is these economies that continue to degrade world-wide resources including further resource exploitation of those very countries that paid the price for the rise of the dominant economies in the first place. International 'aid' particularly in the form of interest bearing monetary loans has sometimes exacerbated the problems: significant falls in export prices have driven developing economies to over-exploitation and depletion of resources to settle these debt payments [193]. Clearly, this increases the environmental problems faced by developing countries and removes the availability of resources from the very people who need them most.

But amid the gloom, there is commitment to change. The UK government has endorsed the action plan of the Human Development Report, published in 1998 by the United Nations Development Programme [194]. One positive outcome of the WSSD in Johannesburg in 2002 was the establishment of new international partnerships between developing countries and the developed world to take action on specific areas of difficulty such as the provision of water infrastructure. However, the problems of Third World debt continue as a disappointing number of developed countries have, as yet, been prepared to write them off. Most recently, the UK Chancellor of the Exchequer, Gordon Brown, has urged international effort on poverty including doubling aid from \$50bn to \$100bn a year [195]. Brown warned that without urgent action by developed nations some nations are possibly 150 years off our targets or the 'millennium goals' for halving poverty, cutting child deaths and of improved education by 2015.

4.3.2 Economics

4.3.2.1 An End to Eco-modernism

The business dilemma – where business tries but fails to reconcile environmental objectives with wealth creation – has resulted in 'eco-modernism' (as discussed earlier in 2.4.6, on page 25). This includes the concept of sustainability being watered down to a more 'acceptable' level as Frankel reports [196]:

> "Third-era corporate environmentalism sent 'sustainable development' through a semantic and conceptual sausage-grinder, whence it emerged as the more palatable 'eco-efficiency'. And that, for the most part, is how it continues to be viewed to this day."

Eco-efficiency is discussed in Figure 24 below. At best, the business dilemma can be resolved through reshaped economic practice, stimulating sustainable activity by making it profitable. Practices are emerging which do just that, or at least position business to take advantage of profiting by gaining the competitive edge. The Natural Step as applied at IKEA has already shown itself to be profitable in terms of resource use and conservation and therefore cost, even within the present economic constraints [197]. Indeed IKEA welcome change for the better [198]:

> "Waste *is* a resource. We welcome regulations that will enable us to manage it to our competitive advantage".

At the least, the economy and economics must be operated in a way which encourages the elimination of all side effects leading to unsustainability – if only through avoided cost. It is of course advantageous that where possible, progress is made in the absence of such harsher influence. A proliferation of tools and approaches has been devised to aid in making this happen in practice, including The Natural Step as discussed.

Sweden has taken sustainable profit to the core of national policy level, seeking to solve the most important environmental problems within a generation – this includes economic incentive and investment to support it [199].

Eco-efficiency is a welcome development engendering the need for material and energy efficiency. The World Business Council for Sustainable Development (WBCSD) defined eco-efficiency as [200]:

> "the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earths estimated carrying capacity."

As discussed on page 49, it is impossible to know what the active constraints to global carrying capacity are, hence the impetus is actually to take efficiency as *far as is possible*. But it is also important to note that eco-efficiency is interpreted many different ways [201]. Preferred measures of eco-efficiency from the point of view of progress toward sustainability would be those for example that reflect efficiency in use of energy and materials or percentage renewable energy used per unit delivered service (as per WBCSD measures). Eco-efficiency measures are often normalised using an economic indicator however. This reduces the benefit of the method since economic value remains an unsustainable influence until such times as the system(s) in question are themselves sustainable. Eco-efficiency measures based on global warming potential or other targeted environmental concerns are not optimal as they emphasise a particular problem rather than encourage solution (see **Figure 25** on page 83).

Both Azapagic and Perdan [202] and Frankel [203] remind us that while eco-efficiency is useful, it is important to remember the *social* dimension in sustainability not covered by such measures.

Figure 24 - Eco-efficiency

4.3.2.2 Trade

Trade issues are of paramount importance in the pursuit of sustainability. Linear flow of resources into the developed world is aggravated by adherence to an expansionist economic model. This model is reflected in the system of national accounts where production of goods is measured as income (as has been discussed in 2.4.2

Expansionism & Systems of National Accounts). The use of this model is no longer confined to industrialised nations however. A recent UN document reports that [204]:

> "the model of economic progress used by the highly developed countries of Europe and North America is now being exported to developing countries. It is increasingly understood to be unnecessarily wasteful, too dependent on non-renewable fossil fuels such as coal and oil...in short, this model is not sustainable and must be changed dramatically if we are to survive."

Daly argues that 'free trade' is anathema to the community [205]. Of the environment, Pearce and Barbier argue that:

> "Although international trade is not necessarily itself a major cause of global environmental problems, the role of trade in reinforcing the market, policy and institutional failures that underlie environmental degradation can magnify the problem substantially."

In the face of criticism on the implications of trade liberalisation and globalisation on the environment, the UK government has indicated that it [206]:

> "supports greater incorporation of environmental concerns into trade policy, so that international frameworks for trade and the environment work in a complementary way".

It is of course action, not rhetoric that will count in the 'greening' of trade. Massive change is needed if mankind is to achieve sustainability: nothing short of revolution [207]. In the end the economic system is unsustainable primarily through its failure to reward sustainable behaviour.

4.4 Promoting Sustainability

4.4.1 The Role of Stakeholders

Significant progress toward sustainability can only be affected through action. At the individual level, there are consumer choices to be made and indeed the decision whether to consume less or even 'down-size' if appropriate. Families and communities have the opportunity to affect change in their choices of energy supplier, housing, and transport. Education is a pre-requisite for generating the required awareness of these choices (see 2.4.3 Ignorance).

At the business and corporate levels, there are significant opportunities to implement product stewardship, promote excellence in innovation and efficiency, close material loops and adopt clean technology – i.e. raising the role of environmental management from regulatory compliance to proactive action (the role of environmental management is discussed further below). While some companies such as Interface (see page 52) are making great strides in these respects, there remains a need for appropriate incentives, market instruments and legislation to promote sustainable material flows within the economy. Regrettably, business response is sometimes trivial, i.e. merely at the level of public relations.

At the national and international levels, governments, organisations and leaders have the opportunity to promote more sustainable trade; promote the use of greener methods of accounting such as the ISEW or GPI; tackle social equity both at home and abroad; and provide the sorts of incentives for business described above. Indeed governments will have to intervene in some cases to redress the effect of unsustainable infrastructure as has been highlighted in this chapter.

Levels of awareness are rising amongst other things through the number of international summits on environmental issues and sustainability. The business dilemma however still remains the greatest obstacle to be overcome. Political and collective will is probably the key ingredient required to provide the necessary impetus for the re-alignment of economics as a driver for sustainable practice. Something the Swedish nation has already embarked on in the wake of their parliamentary decision to 'become sustainable within a generation' [208].

4.4.2 The Role of Environmental Management and its Tools

Environmental management, or taking responsibility for and managing human interactions with the natural environment, can promote sustainable processes but cannot itself change consumer behaviour or politics, nor 'fix' unsustainable infrastructures. Neither can it tackle deep-rooted issues such as inequity in the different economies of the world. Simply put, environmental management cannot govern the scale of change needed to put us on the path to sustainability – this will require a significant intervention by a range of stakeholders as described in section 4.4.1. Notwithstanding these external requirements, the focus of environmental management and its tools appropriately deployed have the potential to procure environmental excellence in the promotion of sustainable processes, services and activities and ultimately the state of sustainability itself.

The following section discusses the approach needed to secure sustainability, develops an operational goal and makes a brief appraisal of the needs for a 'toolkit'.

4.4.2.1 Approach

The framework within which environmental management normally operates has arisen out of a historical development, responding to environmental ills, criticism by environmental organisations and the more recent positive influence of the sustainability agenda. This framework is personified in instruments such as tradable pollution permits, legislation, management tools such as environmental impact assessment, auditing and triple bottom line reporting: it is characteristically problem-orientated. It is evident that a different conceptual framework is emerging – one that is more *goal based* or *solution driven* than the more reactionary problem based approach taken to date and is characterised by tools such as Design for the Environment (DfE), and concepts such as The Natural Step (TNS), Industrial Ecology (IE) and independent certification of sustainable, and in some cases organic, production.

In general the problem and goal-based frameworks must be viewed as complementary and not in conflict: indeed they must be operationalised simultaneously. Both are pertinent, both have their applications. The methods of environmental management arising out of both paradigm frameworks are complementary, as are as feed-forward and feedback control techniques. Protagonists of either view must accept the other: the need to start from the (unsustainable) reality of *problems* faced today is unavoidable, and yet equally we cannot avoid questions about *how* we reach the *goal* of sustainability if we are serious about getting there. It must be stressed however that where problem-orientated approaches are used to the exclusion of the more conceptual elements, that this be done with the goal of sustainability in mind. The importance of positively stated objections in considered in Figure 25 below.

Process control provides a useful analogy for the problem and goal-orientated frameworks [209]. Problem-orientation is the characteristic of feedback control where something has to go wrong first before it is corrected. Goal-orientation (or feed-forward control) requires positive proactive activities to be followed which are designed to achieve the goal. In process control when the feedback loop is prohibitively slow, off-spec material will be produced often and feed-forward control becomes indispensable. For good control and a successful outcome, proper design is vital: no amount of control can compensate for a badly designed system. Thus in order to approach the *goal* of sustainability, we require appropriately designed systems and processes which aim to deliver sustainability. We *seek* to anticipate requirements for sustainability *augmented* by feedback trim (reacting to problem data e.g. pollution or stock levels). This positive approach aims to *deliver* sustainability as far as possible through inbuilt strategic measures and is goal-orientated, augmented by problem-orientated feedback such as from impact data. It would be impossible to reach sustainability by reacting to problems alone.

Sustainability is a goal, thus even where an analytical problem-orientated approach is used it is important to keep this in mind. In terms of language used, objectives for a given task should be stated positively and clearly. Negatives can convey focus in the wrong place. The mind is drawn first towards the problem in order to make sense of the negative (the joke commonly used to demonstrate this is to command of some one: "don't think of a pink elephant!"). Bodenhamer and Hall describe this perfectly [210]:

> "A representation stated in the positive motivates the mind more than a negative representation. Actually, the human mind does not directly process a negative. Suppose some one says to you, 'Don't think of poverty!' To process that statement, you will have to think by mentally representing 'poverty'. You may then have to negate it by crossing it out, letting it fade away, etc., but first you have to *represent* it."

To illustrate the importance of this, consider the following statement.

> 'mankind must not deplete non-renewable resources'

Presenting environmental strategies as 'must nots' draw attention to the problem, rather than the goal or solution. In order to overcome environmental ills it is therefore important to keep the goal in mind while tackling the given problem. In this example then, it would be more appropriate to couch the statement as:

> 'mankind must seek more sustainable use of non-renewable resources through efficient use and timely adoption of renewable alternatives'.

This approach was used in building the strategies in chapter 3 (see page 49 onwards). It is also why the concept of *resource availability* was introduced in chapters 3 and 4 as it better defines a positive outcome than *pollution* or *resource depletion.*

Figure 25 - The Psychological Importance of Positively Stated Objectives

Feedback-based analysis and strategy (the problem-orientated framework) begins with the initial manifestation, measurement and assessment of problems and effects in the environment. This process ends in actions being taken to redress the balance and alleviate the problems. These actions, driven by a pressure to change – either from the shareholder or compliance – are constrained in practice by the business dilemma (consider BATNEEC and BPEO), and by current physical and operational infrastructures (as has been highlighted in this chapter). Another problem with a reactive feedback strategy – both in process control and in the analogy here – is that progress will be slow.

In contrast to problem-orientated approaches, IE, TNS and DfE all have in common a deliberate feed-forward strategy to design sustainability into systems at the outset. These strategies result from a conceptual development rather than from a historical one and are proactive as compared to the reactive approach arising from history. Where these approaches can suffer is that they may appear to be fanciful to companies locked in the business dilemma. So again, while adoption of the goal of sustainability and concepts such as IE are pivotal, it is important to recognise that the starting point for the bulk of businesses is one of unsustainability where reactionary measures (and appropriate tools) are also vital.

Chapter 2 considered barriers to paradigms of sustainability, including the business dilemma. This chapter has added infrastructure issues to this list. Chapter 3 presented a comprehensive and instructive goal of sustainability. What is needed now is an 'operational' absolute – and ultimately an approach – that allows both problem and conceptual frameworks to be implemented in its procurement. This will be developed next.

4.4.2.2 Operational Objective

Achieving sustainability is a comprehensive and formidable aspiration to meet. Despite much debate and at least some progress in consensual understanding of what constitutes sustainability or sustainable development, business remains largely unenlightened about the way in which it can contribute. James reports from a European Commission workshop on the role of environmental management tools in 'business, eco-efficiency and sustainable development' that [211]:

> "there was near unanimity amongst all speakers that the present rate of environmental improvement – and environmental improvement by itself – is insufficient to meet the challenge of sustainable development. More needs to be done in all areas of society including business."

He later continues:

> "An important role for environmental management is therefore to challenge complacency by highlighting what business needs to do in order to be sustainable".

Chapter 3 presented a comprehensive definition of sustainability, and yet it is clear from statements such as those above that if an approach for sustainability can also be further 'operationalised' – both in terms of goals and methods – then this would be a welcome step forward. In order to 'operationalise' the definition presented in chapter 3 for environmental management purposes, it is essential to take account of the challenges faced today (as has been described in chapter 4) as well as the needs of sustainability itself (Chapter 3) – thus allowing implementation of both problem-orientated and goal-based frameworks in its achievement.

Most obvious and central is the need to aim for *sustainable systems*, because as CHAINET[††] sums up [212]:

> "Governments, firms and consumers are embedded in social and economic systems. Thus sustainable development requires consideration of system changes, which implies the redesign of entire systems of production, consumption and waste management."

Thus the goal of *sustainable systems* is defined here as a means to 'operationalise' and deliver sustainable development, which is defined on page 29 as:

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†† CHAINET was a concerted action in the EU Environment and Climate programme (ENV4-CT97-0477). It ran for two years addressing the demand for and use of a range of environmental tools.

> "a system for the meeting of needs in a way that could go on forever, and the state of sustainability is the result of sustainable development achieved globally."

Thus, work toward a *sustainable system* entails looking throughout the life-cycle of a given product or service system, understanding those systems and processes, and seeking ways to *preserve* rather than *infringe* resource availability (and hence welfare). This aim is therefore not one of eco-efficiency; but one of configuring and managing a system in such a way that the system *could go on forever*. While this objective may be difficult to prove in full – because of the issue of access to scarce resources – this a motivating and prescriptive goal in the way that 'total quality' was (see page 65).

Work toward a sustainable system will necessarily involve both problem and conceptual approaches and is necessarily system orientated (it is processes and systems that produce 'goods' and 'bads' in the economy and ultimately welfare – see page 39). In the extreme, this may lead to questioning the long-term viability of the business or system (see Figure 26 below), or perhaps realising an opportunity to move to a service rather than product system. More certainly, it will involve removal of *known* resource availability infringements or RAIs (as discussed on page 35). Moreover, because it is not possible to eliminate all the RAIs of processing and deliver a completely sustainable system when many effects are simply not measurable, application of the Precautionary Principle is required. Indeed, some critical resources are themselves unquantifiable such as biodiversity or assimilative capacity and there is therefore a continuing onus to make systems and processes more efficient *per se*.

Finally it is possible to go further than this delivery of sustainable systems by a positive approach that also *increases* the availability of natural capital or enhances welfare rather than simply ensuring it. For example, if a company has made the transition to renewable energy and yet manages cuts in electricity use through efficiency, there will be increased renewable power available to other consumers. The forest-pulp-paper cycle can positively manage forests to increase biodiversity, rather than simply ensure that re-planting occurs. Where raw materials come from developing countries, its possible to go beyond fair-trade to sponsor the provision of infrastructure such as schools and grants (perhaps though donations to third parties such as charities where more can be done through management of funds raised by the collective effort of many sponsors). In principle, it should be possible to gauge progress of effort to this end through the same framework established for monitoring progress towards sustainable systems in the first place.

In summary, sustainability (as described in chapter 3) is the overriding goal, critically achieved *in part* through sustainable systems. It is difficult to envisage one method that can be employed to help deliver a sustainable system – it is likely that a combination of tools will be required for such an effort and this forms the basis of the next section.

The EEA discusses integration of environmental aspects in strategic planning, including an informative conceptual matrix adapted from work by Hanssen [213]. The matrix is essentially a quadrant comprising four strategies based on environmental performance versus market potential, highlighting paths forward. Critically, one of the strategies is 'drop products as soon as possible'. This of course may be particularly difficult for SMEs with limited or a single product line to accept. Nevertheless, companies that embrace moving toward sustainable systems now – however harsh – may have a better prospect of being in business in the decades to come.

Figure 26 - Strategic Planning

4.4.2.3 A Toolkit for Sustainable Systems

While there is a wide range of stakeholders that must contribute to sustainable development (as discussed earlier), it is ultimately up to *business* to deliver sustainable systems as far as possible. To this end, environmental management tools should be overtly configured and integrated such that they contribute effectively to the achievement of sustainable systems. Ideally a toolkit for environmental management would assist in the delivery of sustainable systems by appraising strategies for sustainability (proactive element); assisting in problem area identification and assessment (reactive framework); and promoting good practice and gauging progress.

Vital elements of any proposed toolkit are:

1. In-built goal of sustainable systems – and promoting sustainability – with all its implications
2. Life cycle extent, through its systems perspective
3. Straightforward applicability.

Efforts to form a toolkit of appropriate tools have already begun. Van Der Vorst, Grafe-Buckens and Sheate present such a conceptual framework for the integration of EIA [214], LCA and Clean Technology; Finkbeiner, Weidemann and Saur discuss LCA within the context of EMS [215]; while CHAINET has focused – amongst other objectives – on appropriate tool selection [216,217].

Potential tools for inclusion in a toolkit comprise, but are not limited to:

- Life Cycle Assessment and conceptually related tools (LCA)
- Life Cycle Management
- Industrial Ecology (IE)
- The Natural Step (TNS)
- Environmental Management Systems (EMS)
- Social Impact Assessment (SIA)
- Total Quality Environmental Management (TQEM)
- Risk Assessment (RA)
- Environmental Impact Assessment (EIA)

Tools such as LCA and concepts such as IE are systems-orientated and therefore well positioned to aid the delivery of sustainable systems. In addition, there are a variety of tools and concepts that might be included in a toolkit but which must be evaluated in relation to their contribution to sustainability. Indeed, this is important since, as CHAINET points out [218]:

> "no single tool can depict all sorts of problems, and all sorts of problem shifting. This situation hampers the use of tools as a support to decision-making and could result in the use of an incomplete or inappropriate analysis, with the ultimate risk of drawing the wrong conclusions".

It is insufficient to merely define toolkit components: it is essential that the work that seeks to develop a comprehensive toolkit also develops and builds in criteria that characterise improvements toward the goal of sustainability and also include indicators of progress. Additionally, *accessibility* of the tools is critical to a definitive toolkit for sustainable systems. If a particular tool is too resource intensive or costly – perhaps only possible with external 'expert' help – this will form barriers to wider adoption and likewise progress toward sustainability. Small businesses have voiced concern over barriers to environmental management in terms of financial and personal commitments [219]:

> "Given that SMEs make up something in the region of 80% of European business, it is critical that they be right at the heart of efforts to improve environmental management in the industrial sector."

This discussion was directed at entry to EMAS, but the concern is analogous. There is little point re-orientating tools for sustainability, seeking to integrate them and trying to engage businesses and other organisations if there are other barriers – particularly cost – that prevent their adoption.

4.4.3 The Contribution of Life Cycle Based Tools

Business needs an ordered and systematic approach to the operationalisation of sustainable development through sustainable systems. Equally important is the need, as described above, to ensure that environmental management tools overtly contribute to the goal of sustainability and sustainable systems. Life Cycle based tools, through their systemic nature are key measures in the environmental management toolkit and are well positioned to help in the quest for a sustainable future. Indeed, *The Johannesburg Plan of Implementation*, from the 2002 World Summit on Sustainable Development calls for the adoption of tools including LCA [220].

Part II of the thesis examines ways in which current LCA methodology can promote a goal of sustainable systems, looking for opportunities for best practice towards the same.

4.5 Conclusions

Sub research question (a) asked:

> **What are fundamental issues that determine the need for environmental management tools including LCA?**

It is evident that consumption and disruption of natural resources – primarily through the behaviour of developed nations – is responsible for threatening both rich and poor societies and precluding the availability of goods and services for future generations. Inequity of global material flows may also be found reflected in levels and nature of poverty in the world. Current methods for provision of food, energy and transportation in the developed world have been shown to be inherently unsustainable and that these problems are rooted within socio-economic issues of infrastructure.

There is a need for all stakeholders from the individual, through business to world leaders to embrace the challenges ahead and make choices that *secure and increase* availability of natural capital, a strong sustainable economy and welfare for the global community.

An operational definition of **sustainable systems** has been proposed as the goal for environmental management work, which is the operationalising of sustainable development as elaborated in this thesis. Life cycle tools – including life cycle assessment – have been identified as key components of an environmental management toolkit for sustainability, given that they explicitly include a goal of sustainable systems.

Part II - Life Cycle Assessment: A Review

"Creating a map is like sculpting a statue. What matters is not only what remains in view, but what has been whittled away"

Anonymous, Human Nature, Jan 1979.

"The map is not the territory"

Korzybsky, A. *Science and Sanity*, 1933.

Chapter 5 - An Introduction to Life Cycle Assessment

5. Objectives

The purpose of this chapter is to provide a brief background history of contemporary Life Cycle Assessment and an overview of the methodology employed. A critique of LCA methodology is made in chapter 6.

5.1 History of Life Cycle Assessment

5.1.1 Definitions

Life Cycle Assessment is the modern day term for an environmental management tool that has been used in different ways and under a variety of names since the late 1960s. Figure 27 lists some of the more popular terms for life cycle studies. There is a confusing similarity between some of the terms that reflect different depths and type of study, especially when reading the literature of the early 1990s. The term 'Life Cycle Assessment' has since been adopted to reflect environmental life cycle studies. Note that the term LCA is used in this thesis *exclusively* to refer to the modern application of the term Life Cycle Assessment.

5.1.2 History of LCA Methodology

It has been suggested that the origin of life cycle thinking can be attributed to the US defence industry [221]. A systems approach was used to consider previously neglected operational and maintenance costs of systems and equipment, allowing high cost, low maintenance systems to be more readily compared with their low-capital counterparts. This has become an established costing technique known as 'Life Cycle Accounting' or 'Life Cycle Costing' (Figure 27).

The birth of contemporary environmental Life Cycle Assessment is commonly referenced as a study carried out by Coca-Cola in 1969. Harry E. Teasley of Coca-Cola conceived a cradle-to-grave study that would quantify the mass, energy and environmental effects of packaging from raw material extraction to disposal [222].

Teasley involved the skills of the Midwest Research Institute (MRI) for the Coca-Cola study and 'Resource and Environmental Profile Analysis' (REPA) was born. REPA was the common term for life cycle studies in the US up until the 1990s (Figure 27).

The Range of Life Cycle Based Tools	
Cradle-to-Grave Analysis	A rarely used term for a study that incorporates the whole life cycle and may or may not include impact & improvement assessments. Often used as a *descriptive* rather than a definitive term.
Ecobalance	Term of European origin similar to the above [223].
Eco-Profile	An assessment often made with a one-stage impact assessment and final judgements made by an expert [224].
Life Cycle Accounting	Financial accounting based on a life cycle perspective [225].
Life Cycle Analysis (LCA)	Term used interchangeably with Life Cycle Assessment in the early 1990s [226]. The term has also been used to refer to studies made using analysis of the inventory alone [227].
Life Cycle Assessment (LCA)	Umbrella term for contemporary life cycle studies, although some might say that life cycle assessment is only that as standardised by ISO.
Life Cycle Inventory Analysis (LCIA)	Term used to refer to studies made using analysis of a life cycle inventory alone.
Life Cycle Costing (LCC)	See Life Cycle Accounting (with which it is synonymous)
Produktlinienanalyse (PLA)	Essentially an LCA that includes "an appraisal of product utility" and includes assessment of social and economic impacts [228].
Resource and Environmental Profile Analysis (REPA)	Term used for life cycle studies conducted in the US between 1970 and early 1990s. Studies included some form of impact assessment, often in the form of an environmental index [229].

Figure 27 - Range of Life Cycle Based Tools

Robert G. Hunt and William E. Franklin of MRI, involved in the Coca-Cola study, were responsible for several REPA studies at MRI, including a study comparing plastic and moulded pulp meat packaging trays on behalf of the Mobil Chemical Company [230]. The emphasis at that time was primarily on solid waste reduction, rather than environmental emissions or energy use. In 1972 the US Environmental Protection Agency had the MRI start an extensive REPA study which culminated with the report *Resource and Environmental Profile Analysis of Nine Beverage Beer Container*

Alternatives published in 1974 [231]. Since the previous REPA studies were of a private nature, this brought REPA into the public domain for the first time.

Franklin set up 'Franklin Associates Ltd.' in 1975, and started conducting REPA studies with Hunt [232]. The EPA lost interest in REPA at that time, wishing to focus on more general issues than specific product life cycles. Public interest in comprehensive life cycle studies was also slight between the mid-1970s and 1988. Franklin Associates Ltd. carried out most of the studies during that time, with many having a strong emphasis on energy during the energy crisis of the 1970s. However, a significant British text published during this time (1979) was the 'Handbook of Industrial Energy Analysis' co-authored by I. Boustead and G.F. Hancock [233]. While it is not a textbook on REPA, it does provide methodology for energy analysis from a life cycle perspective and has become a heavily referenced text, particularly in the LCA field. The book represents the UK's first experience of the life cycle perspective.

1988 saw what Hunt and Franklin describe as 'a dramatic re-awakening of environmental consciousness in the U.S.', followed by a significant increase in both the number of life cycle studies being conducted and public interest in the subject [234]. Curran refers to 15 studies being conducted in the U.S. up until 1975, with the total rising to more than 100 in the period 1988 to 1991 [235]. Most of the studies were privately funded and the results unpublished. Of the studies that *were* published, most were studies of packaging systems.

In May 1990, the potential role of REPA in U.S. environmental policy was publicly debated in a forum held by The Conservation Foundation in Washington, D.C. [236]. In August of that year, the Society of Environmental Toxicology and Chemistry held the first of several workshops on life cycle studies. The workshop was held at Smugglers Notch, Vermont and is significant because the workshop report, *A Technical Framework for Life Cycle Assessment* (published in 1991) [237] has become one of the most referenced texts on life cycle inventory guidelines. It was at this time that the term 'Life Cycle Assessment' was adopted to refer to life cycle studies rather than REPA. One of the main findings of this workshop was that LCAs should consist of three separate components, namely [238]:

1. Life Cycle Inventory;
2. Life-Cycle Impact Analysis; and
3. Life-Cycle Improvement Analysis.

The US Environmental Protection Agency took a renewed and active interest in LCA at that time sponsoring two significant projects during 1991. The first project was contracted to Battelle and conducted between August 1990 and May 1991. The final report, co-authored by members of Battelle, Franklin Associates Ltd., and the US EPA Risk Reduction Engineering Laboratory entitled *Life Cycle Assessment: Inventory Guidelines and Principles*, was published in 1994 [239]. The second US EPA research programme was carried out at the National Pollution Prevention Centre at the University of Michigan during January 1991 to December 1991. The report was first released in January 1993 entitled *Life Cycle Design Guidance Manual: Environmental Requirements and the Product System* and published in February 1994 with a new *Design for the Environment: Product Life Cycle Design Guidance Manual* [240]. It should be made clear however, that while this manual is based on life cycle thinking it does not contain guidelines for LCA *per se*.

The Society of Environmental Toxicology and Chemistry (SETAC) held two LCA workshops during 1992. The first was on life cycle impact assessment and was held in February at Sandestin, Florida [241]. At this workshop the framework for LCA agreed upon at the previous workshop of 1990 was re-affirmed and a fourth component 'Goal Definition and Scoping' was added. This fourth stage is intended to be dynamic in nature and is best represented diagrammatically (see Figure 28). The workshop was a discussion of state-of-the-art in life cycle impact assessment and the report is not intended to be a definitive guide on impact assessment (at the time of writing there is still no one single widely adopted or accepted impact assessment methodology). The report *A Conceptual Framework for Life-Cycle Impact Assessment* was published in 1993 [242].

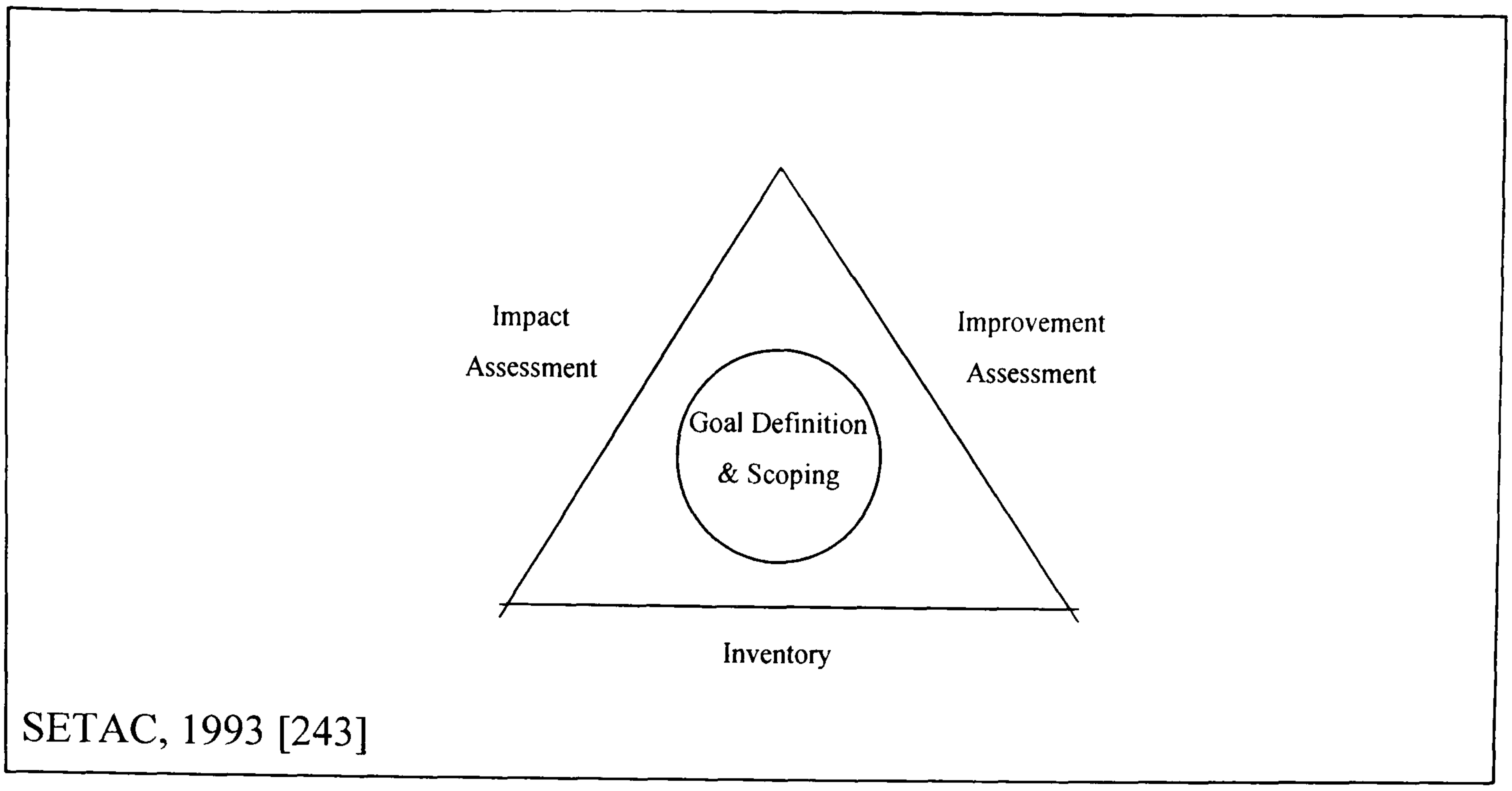


Figure 28 - Goal Definition in the SETAC LCA framework.

The second SETAC LCA workshop of 1992 concentrated on data quality and was held in October at Wintergreen, Virginia. The report *Life-Cycle Assessment Data Quality - A Conceptual Framework* was published in 1994 [244].

The North American and European SETAC LCA advisory groups met in March 1993. The workshop, held in Sesimbra, Portugal, was used to develop a 'Code of Practice'. The workshop report *Guidelines for Life-Cycle Assessment: A 'Code of Practice,'* published in 1993 [245] is sometimes referred to as the 'LCA Bible" [246].

Other LCA guidelines during the 1990s include the publication of the 'Dutch guidelines' on LCA, *Environmental Life-Cycle Assessment of Products. Guide and Backgrounds* from CML, Leiden University, The Netherlands (1992) [247]; the *Nordic Guidelines on Life-Cycle Assessment* (1995) developed by Swedish, Finnish, Danish and Norwegian authors [248]; *Life Cycle Assessment: What It Is and How to Do It,* from the United Nations Environment Program (1996) [249]; and The European Environment Agency's *Life Cycle Assessment: A Guide to Approaches, Experiences and Information Sources* (1997) [250].

There have been a number of initiatives to standardise LCA methodology. In spring of 1994 the Canadian Standards Association released the world's first national LCA guideline *Z-760 Environmental Life-Cycle Assessment* which was 'intended to assist industry in environmental decision-making, to aid in development of global environmental standards and to provide in-depth information on LCA methodology' [251]. The most recognised standards are however those developed by the International Standards Organisation (ISO). A number of working groups were set up to investigate different areas of LCA methodology that culminated in the publication of several standards (and a number of related supporting documents) [252]:

- **ISO 14040** Environmental management – Life cycle assessment – Principles and framework (1997) [253].

- **ISO 14041** Environmental management – Life cycle assessment – Goal and scope definition and inventory analysis (1998) [254].

- **ISO 14042** Environmental management – Life cycle assessment – Life cycle impact assessment (2000) [255].

- **ISO 14043** Environmental management – Life cycle assessment – Life cycle interpretation (2000) [256].

Note that with the advent of ISO standardisation, improvement assessment turned into 'interpretation' (see 5.2.4 on page 103). Since the publication of ISO standards, development of LCA methodology has continued. Ongoing development effort includes areas such as allocation [257] and impact assessment [258,259]. Recently, CML published the *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards* (2002) [260].

Most recently, there has been increasing attention on life cycle management (LCM) as demonstrated through the current UNEP-SETAC initiative [261,262].

5.2 Overview of Typical LCA Methodology

5.2.1 Overview of LCA Goal Definition & Scoping

LCA has been applied in a number of different ways and for various objectives. The goals of an LCA should be reasonably clear, since some definition of goal usually precedes a study of any nature. The object of the scoping exercise is to interpret the goal(s). Historically common goals of LCA include:

1. Determination of the most environmentally benign of two or more consumer products (for example comparing a reusable product with a disposable equivalent);
2. Determination of the more environmentally benign of two or more processes (for example comparing incineration and landfill options for a given waste).
3. To examine the environmental impacts from a given product/process/life cycle (sometimes known as hot spot analysis).
4. To determine criteria pertinent to a product certification programme (or for public policy or legislative requirements).

There are often financial, temporal, manpower and other limits to an LCA; scoping is used to determine how best to achieve the goals of the study in light of such constraints. The scoping exercise is often used to set initial requirements such as *study boundaries*, the *specificity* of the study and so on. These criteria are likely to change as the study progresses and although scoping starts before data collection, the exercise is usually continued right through the LCA.

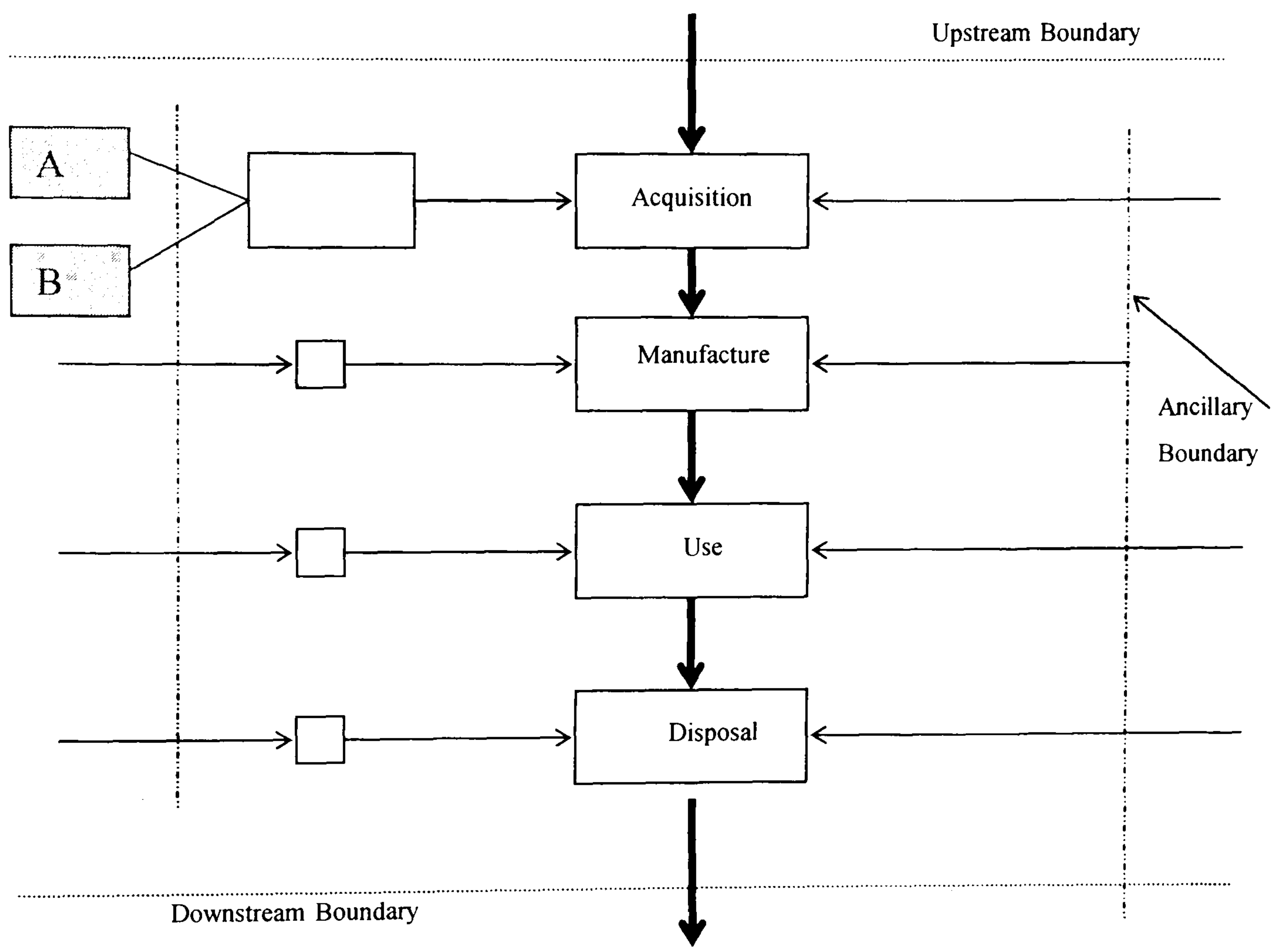
5.2.1.1 Study Boundaries

'Study boundaries' is a term covering all the boundaries that encompass the study including financial and resource constraints and the geographical or process boundaries that describe the life cycle in question. The term 'system boundaries' is used to be more explicit about process boundaries, but sometimes the term 'study boundaries' is (incorrectly) used to refer to process boundaries in particular and this causes confusion.

System boundaries describe the extremities of the system boundaries on the cradle-to-grave route (see Figure 29). Note that a 'full' LCA would not have upstream and downstream boundaries as such, since the natural environment is both cradle and grave.

What can be more difficult is choice of ancillary boundaries, i.e. where to cut off data collection of materials incidental to the main production route. For example, the processes A and B are outwith the study's current system boundaries in Figure 29.

'Level' boundaries are difficult to describe diagrammatically as they relate the depth of the analysis. For example, when studying transport, it would be possible to record the vehicle manufacture, tyre wear and fuel consumption; to record merely the fuel consumption; or any combination of these.



Note that the thicker arrows delineate the main production route.

Figure 29 - Boundaries in LCA

5.2.1.2 Data Specificity

Data used in LCA studies falls broadly into two categories as regards specificity:

1. *Specific Data* obtained directly from products or processes in the real world.

2. *Generic Data* which may come from industry average data or public/proprietary databases.

In practice, LCA studies often use both data types. Where the distinction is made between foreground and background systems, process specific data is used in the foreground and more generic data in the background [263].

5.2.2 Overview of Inventory

Demarcation between initial scoping and the inventory is somewhat blurred. Initially there is likely to be a crude idea of the system boundaries and one of the first steps before gathering data is to draw a life cycle diagram and provide some more detailed boundaries. These boundaries will change as data gathering progresses because of data uncertainties, gaps, new information and so on.

The life cycle diagram is drawn using a systems approach whereby the life cycle is pictorially described as a number of black box processes. LCA authors and practitioners often describe inventories using 'systems analysis'. Systems analysis is conceptually quite simple: start with the simplest diagram that describes the life cycle and continue to break this down into successively smaller systems until the level of detail required for the inventory is achieved (see Figure 30).

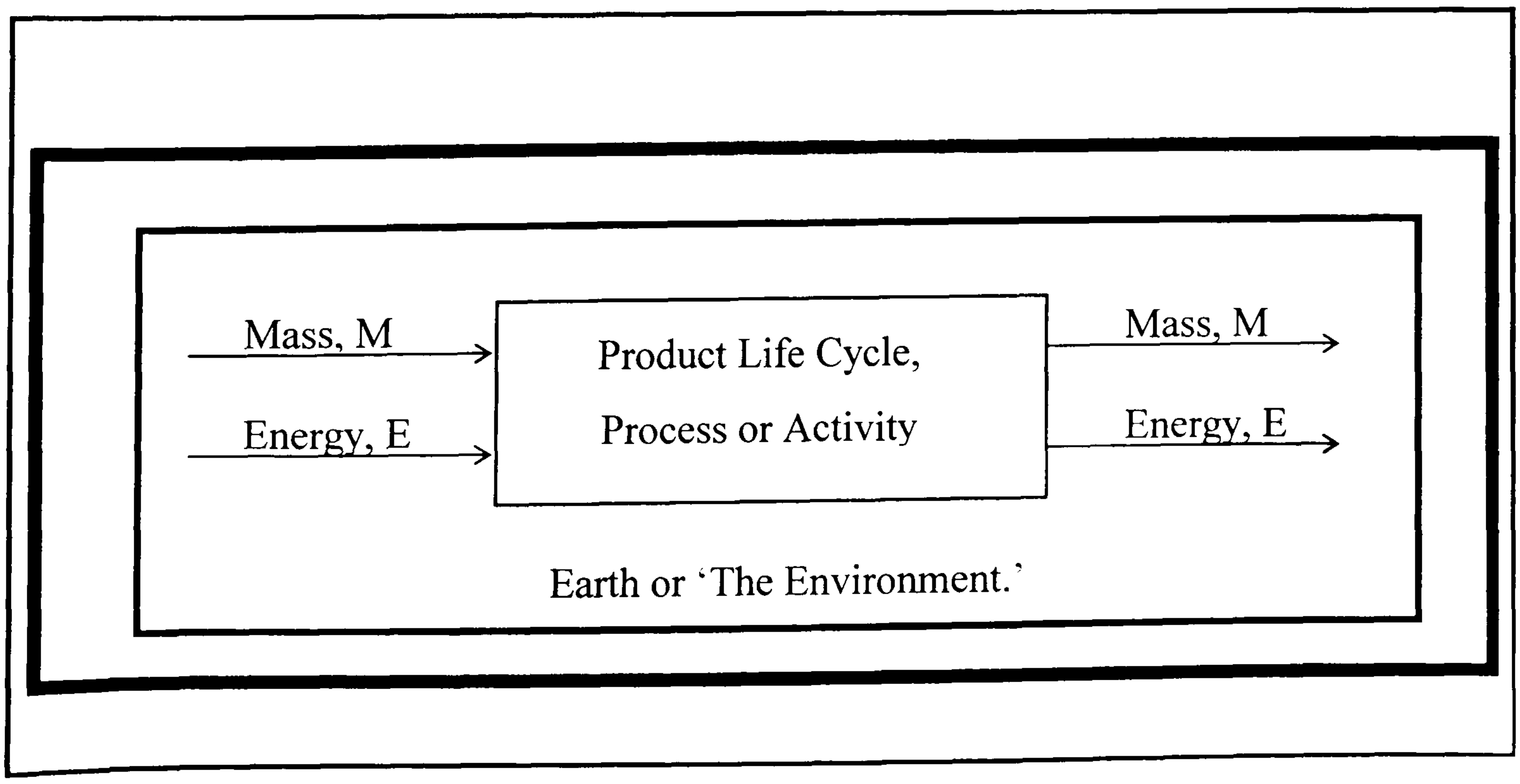


Figure 30 - Systems Analysis

The simplest life cycle diagram is just a black box with inputs and outputs (Figure 30). While this diagram may seem to be 'stating the obvious' it illustrates an important point that *all* inputs taken from the earth are at some point returned to the earth ('the earth' obviously includes land, air and water), i.e. conservation of mass and energy applies. A formal LCA requires that this full 'cradle to grave' perspective is employed: by strict definition a study using narrower longitudinal boundaries is not a Life Cycle Assessment.

'Life cycle stages' of *raw material acquisition, manufacturing, use, and waste management* are often used as the first level of detail. From here, each stage is taken in turn and described in more detail. Clearly some stages will be far more detailed than others, for example a chemical plant may be very complex and require diagrams of its own (note that in such a case, black boxes are sometimes used to avoid details that present an unnecessary level of detail to an inventory).

After drawing up a life cycle diagram, data is collected and is generally stored on computer spreadsheets or databases. As mentioned above, it is important to recognise that as the data collection process proceeds, the system boundaries may well have to be changed.

5.2.3 Overview of Impact Assessment

Following an inventory, normally one or a blend of three things is done:

1. *Ways are sought to minimise the environmental emissions recorded in the inventory.* This is often termed the 'less is best' approach and is essentially stepping straight from the inventory to improvement assessment.
2. *The emissions are compared to a similar life cycle.* This applies mainly to comparative LCAs, such as considering a reusable against a disposable product or comparing a baseline to potential improvement options – the 'prospective LCA'.
3. *A full or partial impact assessment is made.* Life Cycle Impact Assessment (LCIA) seeks to translate the material and energy flows described in the inventory in to a profile of different environmental themes. Normally this is done in a way that represents potential, rather than actual impacts. The reason for the relative, rather

than absolute approach is to provide contributions relative to the function of the system [264]. Several methodological steps are normally taken during LCIA (but not all are necessarily followed). SETAC proposed classification, characterization and valuation [265], and this was largely adopted by the ISO standard [266], although the terminology differs. Standardisation by ISO has not stopped development in this area, indeed impact methodology remains an ongoing research effort. SETAC has recently published *Life-Cycle Impact Assessment: Striving towards best practice* to this end [267].

5.2.4 Interpretation or Improvement Assessment?

Improvement assessment was presented as a formal methodological step by SETAC in the early 1990s [268], but was declared 'not yet documented' in 1993 [269] and later substituted with 'Interpretation' [270]. Fava indicates that this was because [271]:

1) an LCA can be used for other purposes than just improvement; and
2) there was confusion that the process of implementing improvements was implicit to the LCA (when usually this would be outside the LCA process).

With improvement being seen as an application of LCA, and not part of LCA [272], the explicit focus on improvement assessment has thus faded away over the past decade [273]. Saur tells us that interpretation *is not* improvement assessment as defined by SETAC, but instead a step that provides 'reliability and meaning to the LCA study performed' [274]. ISO define interpretation as [275]:

> "a systematic procedure to identify, qualify, check and evaluate information from the results of the LCI and/or LCIA of a product system, and to represent them in order to meet the requirements of the application as described in the goal and scope of the study."

Interpretation does not preclude improvement assessment: it just doesn't demand it unless it were part of the study goal and objectives. Work into improvement assessment has been limited [276], but improvement methodologies have been published. The 1992 Dutch guidelines on LCA included 'marginal analysis', but Heijungs and Kleijn report that this has not generally been applied [277]. More popularly, linear programming has been used to optimise life cycle models – see for example Azapagic & Clift [278,279], and Bloemhof-Ruwaard, Van Wassenhove, Gabel and Weaver [280].

Interpretation and improvement assessment are discussed further in the next chapter.

5.3 Conclusions

This chapter has provided the background to a tool that, while still in development, has a great deal of potential to help make informed decisions about the life cycle of a given product or process. It has such great potential because the tool:

- is holistic;
- comprehensive and systematic;
- can be used to identify key areas of concern;
- minimises potential for 'problem-shifting';
- facilitates better understanding of effects on other life cycles.

Chapter 6 – Review of LCA Methodology

6. Objectives

Sub research question (b) asked:

> **How effective is current LCA methodology in promoting sustainable product systems?**

Chapters 6 and 7 answer this question by examining LCA methodology and approaches used. The primary objective of this chapter is to examine the suitability of LCA methodology in the pursuit of sustainable systems as defined in Part I.

6.1 Introduction

The last chapter gave a general overview of life cycle assessment methodology. This chapter begins the answer to sub research question (b) by determining whether LCA methodology promotes the goal of sustainable systems in its assessment of products and processes (note that full conclusions are drawn in Chapter 7.

Many of the methodological elements of LCA represent its use as an analytical tool and therefore do not explicitly promote or antagonise any goal set by the practitioner. However, some LCA features are goal dependent and much of this review will identify elements that *implicitly* promote or antagonise sustainability.

6.2 LCA – Tool, Concept or Process?

It is useful to begin by considering exactly what LCA is considered to be. There is a general consensus in the literature that life cycle assessment takes a holistic approach to the evaluation of potential environmental impacts associated with a product or process of interest; and that the term 'life-cycle' refers to a cradle-to-grave perspective. This consensus has been expressed both in the early SETAC definition of life cycle assessment [281] and the internationally recognised ISO standard [282]. Beyond this, however there is much less agreement about what LCA actually *is*.

SETAC refer to LCA as a process [283]; ISO call it a technique [284]; UNEP says it is a tool [285]; and others refer to it as a method [286]. The European Environment Agency describes LCA as a *family* of life-cycle based tools, applied as a conceptual framework or tool [287].

These distinctions are subtle yet important in that they set the context and the expectation for the LCA application and hence affect its output or results. Cowell, Hogan and Clift discuss the development of LCA-based methodologies, and point to a historical trend towards its use as a tool [288]:

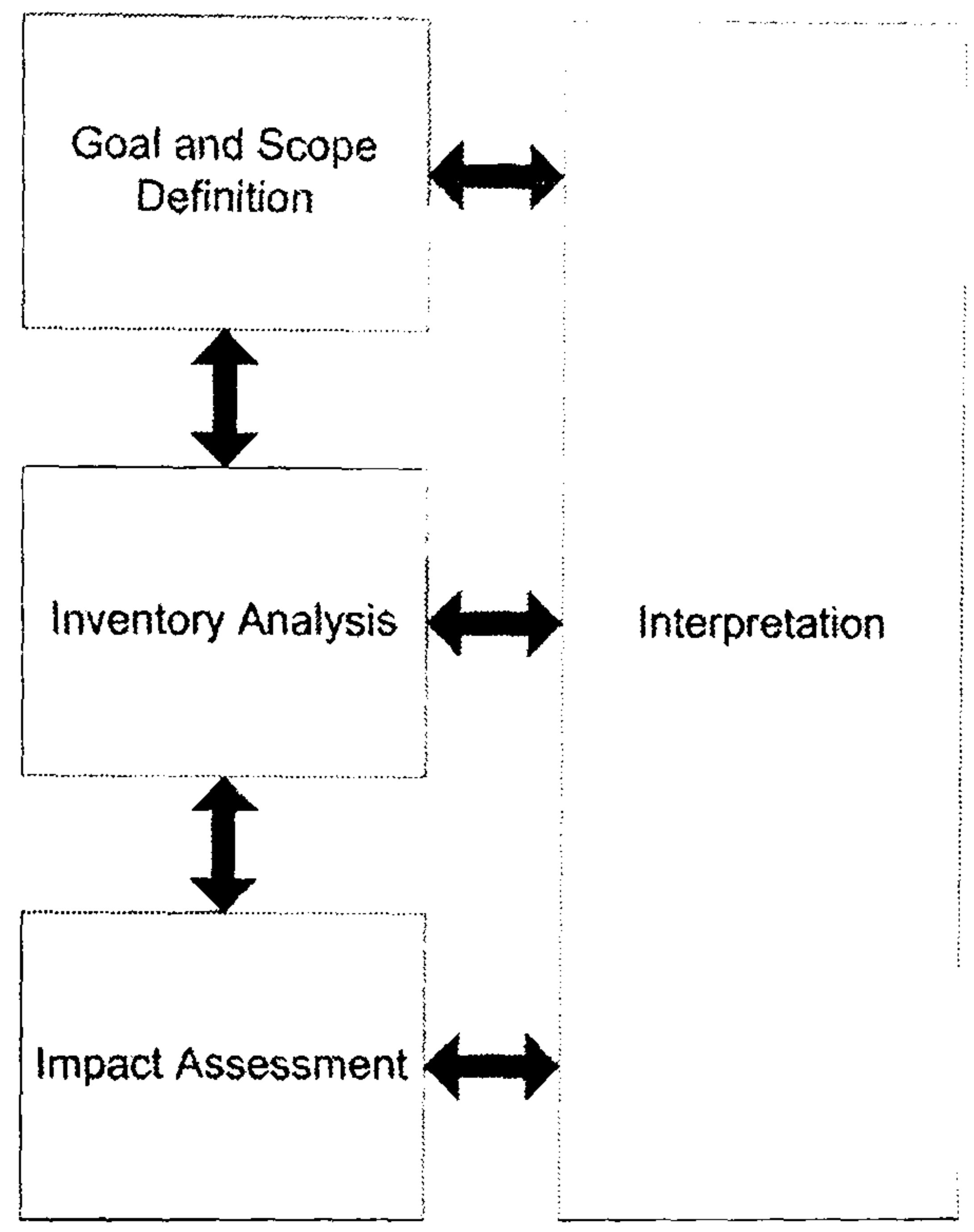
> "Up to the present time, the main focus of research has been on developing LCA as a tool rather than a process. Hence, there has been an emphasis upon assessment of potential environmental effects".

LCA classification is also made according to its use, for example:

- whether it is retrospective (descriptive of the past) or prospective (expected or proposed changes) – see Guinée *et al* [289]; and
- whether it is attributional (describing flows within a system) or consequential (dealing with changes to flows within a system) – see Frischknecht [290].

A significant step in the quest for some kind of standardisation has been the internationally accepted standard framework for LCA, as has been set out in ISO14040 [291]. The framework embodies much of the work that preceded it, by SETAC [292,293,294], CML [295] and the Nordic Council of Ministers [296] amongst others. The ISO framework recognises that LCA as a whole is still at an early stage in development. ISO 14040 and related documents allow the practitioner to choose their own goal and application; indeed, it states that the applications of LCA for decision making is strictly outside the scope of the LCA and the standard itself.

Beyond the above, it is ultimately the goal to which the LCA is applied that finally defines how the LCA is deployed and which model is used (also see goal definition and scoping below) [297]. The ISO framework defines four methodological steps which have become accepted as the basic features of LCA [298] (see Figure 31 - ISO below). According to the ISO text, these steps – like the LCA guidelines that preceded it – are intended to be iterative in nature [299]. These four methodological phases are considered in sections 6.3, 6.4, 6.5, and 6.6 respectively.



Source: Adapted from ISO 14040 [300]

Figure 31 - ISO 14040: Phases of the Life Cycle Assessment Framework

6.3 Goal Definition and Scoping

The goal definition and scoping step of LCA methodology is used to form the objectives and constraints of a study. SETAC first added this formal step to its LCA methodology in the early 1990s [301]. The concept was later developed by SETAC [302] and has been encapsulated in the ISO 14041 standard [303]. Azapagic notes that the differences between SETAC *guidelines* and ISO *standards* are in fact few [304].

Various authors provide guidance on the goal definition and scoping step. Lindfors *et al* were early to define requirements and decisions to be made for this step [305]. Frischknecht, through the LCANET initiative, describes different potential LCA applications and the data needed to support them – whether specific or generic [306]. Guinée *et al* have sought to operationalise the ISO guidelines through a handbook based on the ISO standards [307]; providing a step-by-step advice with a particular focus on method which they say is 'intended to support decisions with respect to a changing situation' [308].

The goal definition step is critical to the LCA as it defines the LCA purpose or question to be answered, and has a strong influence on the result of the LCA [309]. The scope in terms of initial system boundaries, assumptions and other limits such as spatial and temporal dimensions, functional unit and data quality are all specified at this stage. The goal definition and scoping exercise ultimately defines the direction of the study and the benchmark with which the study will later be appraised in the Interpretation stage. The functional unit definition is important as it describes the system under study. Azapagic defines the foreground and background subsystems based on the functional unit as follows [310]:

> "The foreground system is defined as the set of processes directly affected by the study delivering a functional unit specified in Goal and Scope Definition. The background system is that which supplies energy and materials to the foreground system, usually via a homogeneous market so that individual plants and operations cannot be identified."

This is a useful distinction because, as Azapagic writes, it is therefore possible to distinguish process specific data in the foreground system from average data for the background.

At a general level, the methodological elements of goal definition and scoping cannot be criticised for promoting or antagonising the goal of sustainability or sustainable products. It is the LCA purpose or question being addressed that is of interest. An LCA study that does not explicitly have sustainability in its goal definition does not necessarily fail to promote some sustainability in its method or findings. The influence of sustainability on LCA and goal definition is further considered in chapter 7.

There has also been some effort toward 'simplified' or 'streamlined' LCA methodology in recent years – see for example Christiansen *et al*, *Simplifying LCA: Just a Cut? SETAC EUROPE LCA Screening and Streamlining Working Group* [311]. and *Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America*

Streamlined LCA Workgroup [312]. The aim of such an approach is to focus the study on key areas of interest whilst omitting areas of limited interest. These approaches include similar techniques used in narrowing the study scope of the problem and often include the elimination of parts of the life cycle or focus on a particular impact category. An elimination of life cycle steps may not make much difference in terms of a given study purpose or question, but should perhaps be treated with caution when using the LCA explicitly towards sustainable systems definition. Such omissions may mean that opportunities to affect significant improvement toward sustainability may be overlooked. Even if elements of the whole life cycle are described in a more general fashion the fact that the whole system is considered will present opportunities for improvement otherwise missed. This is especially true when used in an LCA approach for strategic action with respect to sustainability as described in part I of the thesis.

6.4 Inventory and Inventory Analysis

The second step in LCA is inventory (and inventory analysis) and is the most well documented phase in the LCA literature. According to ISO, this phase involves the 'data collection and calculation procedures' [313] and is of key importance since this data will form the basis for the study. Inventory is also intimately tied to the scoping exercise since data collection and other issues may lead to refinement or redefinition of the system boundaries. ISO define several steps in the inventory phase which may be summed up as [314]:

- data collection / validation
- refining system boundaries / relating data to the functional unit
- allocation

On data, Lindfors *et al* note that it is not always possible to choose between data sources and the practitioner may have to take the best (or only) data available [315]. This situation has perhaps improved since the mid 1990s with the development of various databases for life cycle inventory data (e.g. SPOLD).

Data quality is especially important in the LCA. Reporting on a workshop on LCA data quality Fava *et al* noted that [316]:

"Data quality was defined as the degree of confidence in individual input data and in the data set as a whole and ultimately in decisions made by using the data. The reliability of LCA conclusions as final results depends on the quality of the input data and the way they are processed into results using an LCA methodology."

Data quality is important whatever the goal of application. Boundary setting and allocation also have an effect on conclusions drawn for a given LCA. Weidema, for example, reports on misleading environmental declarations made on the basis of boundary choices [317]; Wolf *et al* report that wrong conclusions could be drawn without an appropriate allocation method in the case of recycling steel [318]; and Seungdo and Bruce report that sensitivity analysis showed that choice of allocation procedures had the greatest impact on a study of ethanol as a fuel [319].

The iterative steps of goal definition / boundary setting / allocation may be inseparable in some cases. The functional unit defines the system to be studied [320] and the need for allocation stems from the requirements of the study goal and is also inherently related to boundary selection. Lindfors *et al* discuss various allocation techniques [321]. They do not recommend any single allocation procedure as the best, something which is probably impossible to do. Frischknecht – through LCANET – discusses different potential allocation procedures in relation to the goal of the study, summing up that [322]:

"A consensus on the actual application of the ranking order for allocation procedures (i.e. which causality to use in which case) has not yet been achieved. Some people argue that the choice of allocation procedure is a political and not a scientific one. If this should be true, the choice includes a subjective or maybe even arbitrary component."

Tillman also writes that [323]:

"allocation procedures have been among the most heavily debated issues of life cycle inventory (LCI) methodology" and there certainly remains debate on such procedures in the more recent literature. While allocation procedures continue to become more sophisticated, Frischknecht reports that, for example, allocation in joint production, i.e. allocation between two or more products, remains 'unresolved' and concludes that [324]:

> "It has been shown that allocation in joint production is mainly performed for reasons of competitiveness and not for reasons of finding the economic or environmental 'truth'. That is why allocation in joint production entails inevitable value judgements that can have severe consequences for the outcome of an LCA and the conclusions drawn from it".

Although allocation methodology is embedded in much LCA literature it is not necessarily core to a basic LCA framework. Quantitative LCA used as an analytical support tool may require these elements, but LCA applied more conceptually does not [325]:

> "life cycle thinking is a way of addressing environmental issues and opportunities from systems or holistic perspective. In this way of thinking, a product or service system is evaluated or designed with a goal of reducing potential environmental impacts over its entire life cycle. The essential difference is that life cycle thinking does not generally normalise the results to a functional unit, as is done as part of an LCA study".

Weidema and Norris have also demonstrated how to avoid allocation through system expansion [326] and this is presented as the *preferred* means of allocation procedure in ISO 14041 [327]. Widening the boundary wherever feasible might make sense in promoting sustainable systems, but extending boundaries to avoid allocation may be of little value if the problem is with the system itself [328]. The decision whether to employ allocation at all and if so, which procedure to use needs to be made on a case-by-case basis. Choice of allocation procedure – essentially choice of a model – should be reasoned scientifically as Frischknecht suggests [329]. The final selection ultimately carries an unavoidable subjective element, while reality is not bounded by any model assumptions or constraints which are necessary for answering study questions.

The need for allocation is largely dictated by the need to draw a system boundary to limit the study, which stems ultimately from goal definition (see trade-off described above). If the system boundaries were set wide enough, there would be no need for allocation at all. Indeed there is literature on the very matter of expanding boundaries so as to avoid allocation completely (as per Weidema and Norris above). Allocation methodology, like goal definition and scoping, does not itself promote or antagonise sustainability. It does however, narrow the focus on the system(s) of interest, further refining the system in relation to the study question or objective. This reinforces the need for care in setting the study purpose – or question to be answered – if it is to promote sustainability explicitly. Application of allocation can also present a degree of complexity which puts off many potential users of LCA and while allocation is embedded in much LCA methodology, the level of complexity in a given study should be consistent with the goal.

6.5 Impact Assessment

Impact assessment is central to an ability to perform analytical evaluations for decision making within LCA. More specifically – in the context of this thesis – it enables the assessment of improvement options and the appraisal of progress with respect to the goal of sustainable systems. Life cycle impact assessment (LCIA) is perhaps the most heavily debated area of LCA methodology at present – see for example the report on the Brighton conference [330] (2000), and the email debate [331] that resulted in the chapter entitled *The Conceptual Structure of Life-Cycle Impact Assessment* in SETAC's *Life-Cycle Impact Assessment: Striving Towards Best Practice* [332] (2002). Given the complexity of the issues and weight of opinion involved, the debate is likely to remain open for some time to come.

ISO 14042 [333], the international standard for life cycle impact assessment, is thought to embody some 250 man years of effort [334]. ISO 14042 defines impact assessment as aiming to [335]:

"examine the product system from an environmental perspective using impact categories and category indicators connected with the LCI results. The LCIA phase also provides information for the life cycle interpretation phase".

In its simplest form, impact assessment establishes a relationship between the cause of environmental impact and degradation effect(s). This chain of events – or environmental pathway – is built on scientific knowledge, but is made on the potential to cause harm, not actual effect (in the way that EIA would measure). Such an impact category is usually defined by a category indicator (such as global warming potential).

Impact assessment methodologies can be initially demarcated into two broad categories: (1) single step methods (such as Ecoscarcity and EPS-system) and (2) multi-step methods (such as found within SETAC and ISO frameworks [336]). The single step methods attract criticism for aggregating all impacts to a 'single score' [337] or for being tied to economic and political issues with the inherent problems of subjectivity [338]. The multi-step approach was developed to separate the *objective* from the more *subjective* analysis elements [339] – such as weighting. The weighting step is in fact voluntary under the ISO framework (as discussed below). There are indeed many impact methodologies that suit different needs and purposes. Subtler differences may be found in the level of data aggregation employed (see for example *Life Cycle Impact Assessment Based on Decision Analysis* [340]), or in whether a 'midpoint' or 'endpoint' in the cause-effect chain is used as the indicator [341], and in what weighting approach is taken (see review of weighting methods by Finnveden [342]). Recently, approaches that broaden the traditional LCIA framework remit have been proposed (see for example Azapagic and Perdan, *Indicators of Sustainable Development for Industry* [343]).

In keeping with previous methodologies presented by SETAC and others, ISO essentially use *classification*, *characterisation* and *valuation* steps to link LCI data to potential impact categories for assessment purposes. Again, like SETAC and others, ISO uses a *relative* approach based on functional unit to assess the *potential* to cause impact [344], rather than an assessment of actual or 'absolute' impact as in the case of classical environmental impact assessment or EIA [345]. The selection of impact categories, the assignment of LCI results to categories (classification) and the calculation of indicator 'results' (characterisation) are considered mandatory elements of ISO 14042, with elements such as grouping and weighting (valuation) being optional. Note that ISO 14042 actually prevents the use of weighting methods in comparative assessments disclosed to the public [346].

ISO 14042 is itself an open framework and is not prescriptive about impact categories. However, LCA has developed from a problem-orientated perspective – or has been driven by the challenge of environmental pollution and degradation problems [347]. This may be found reflected outside ISO 14042 in *prescriptive* impact assessment methodologies as Azapagic writes:

> "A number of methods have been suggested for the identification and quantification of environmental impacts; however, the problem-orientated method, developed by Heijungs *et al*, is the most widely used. In this approach, the burdens are aggregated according to the relative contributions to specific environmental effects, such as global warming potential, acidification, ozone depletion etc. For instance, CO_2 is a reference gas for determining the global warming potential of other related gases, such as CH_4 and other VOCs"

While ISO allows such selection of category indicators, it has become the norm to use a predetermined list as Jensen *et al* observe [348]:

> "Numerous environmental categories have been proposed for life cycle impact assessment. Most studies will select from these previous efforts and will not define their own categories".

A typical impact category list may look like that presented by Lindfors *et al* [349] (see Figure 32 below).

1. Resources – Energy and materials
2. Resources – Water
3. Resources – Land (including wetlands)
4. Human health – Toxicological impacts (excluding work environment)
5. Human health – Non-toxicological impacts (excluding work environment)
6. Human health impacts in work environment
7. Global warming
8. Depletion of stratospheric ozone
9. Acidification
10. Eutrophication
11. Photo-oxidant formation
12. Ecotoxicological impacts
13. Habitat alterations and impacts on biological diversity

Adapted from Lindfors *et al* [350]

Figure 32 - List of Impact Categories

There is not yet consensus on a preferred list of indicators nor agreement on where the indicator on the cause-effect chain should lie. Indeed, Life Cycle Impact Assessment (LCIA) as a whole does not, as yet, find the same level of maturity that inventory methodology enjoys. With the publication of ISO 14042, there has perhaps been more interest in how methodology fits into the multi-step framework – including single step methods hitherto proposed [351]. ISO 14042 is an open framework without being prescriptive about impact categories (see below) and specific methods such as valuation. Yet in spite of this some LCA developers – under the auspices of SETAC – are pushing for a 'best available practice', as discussed by Hertwich, Pennington and Bare [352]:

> "Companies and practitioners… require off-the-shelf characterisation and weighting factors… In our view, some elements in the competing methods represent different judgements about both what goes on in nature (the cause-effect chain) and the importance of different valued items. We accept, however, that decision makers have neither the need

> not the capacity for understanding these issues in their full complexity, and that they would be better off with a single approach. We hence strive to develop a best available practice for impact assessment".

Another key driver for a single method – also discussed by Hertwich, Pennington and Bare – is the desire for ease of comparability [353]. Lagerstedt, Luttropp, and Lindfors write [354]:

> "Comparative assertions were seen as one of the main applications of the LCA methodology in the early 1990s and fear of misuse was the reason behind the development of a strict methodology in SETAC and later in ISO".

Indeed much LCIA development effort has included the support of LCA as an analytical tool for comparison studies since the early 1990s [355]. There have been some clear differences of opinion on issues involved – particularly as regards weighting [356]. On the one hand, there is the open framework approach where impact criteria and methodological elements are selected in accordance with the nature of goal definition within the study (but *weighting* is to be *avoided* in comparative mode where results are to be made public – see ISO 14042 [357]). On the other hand, there is a desire for a single best practice [358] and in this context there is increasing popularity for the use of end-point indicators in comparative LCAIs because such approaches actually make weighting *easier* [359].

Moves toward a 'best available practice' may not seem directly relevant to the companies and practitioners who purchase software for such analysis. However, the debate and development described above is indirectly pertinent to users since it may be found reflected in LCA/LCIA software and datasets. Although such debate is necessary and relevant to the continuing development of LCA as an analytical decision-support tool, it is not necessarily helpful to the practitioner uninterested in making system comparisons. The comparison debate has perhaps less relevance to those companies and practitioners more concerned with internal use of LCA for hot spot analysis (i.e. identification of particular problem areas for improvement). For example, using sustainable systems as a predefined goal asks 'how do we make this life cycle sustainable' and not 'is this life cycle *x* better or worse than life cycle *y*'. As discussed further below, this context places quite a different emphasis on the needs of LCIA.

Traditionally, many methodologies have taken a problem orientated approach with a heavy focus on toxicological aspects of impact assessment [360,361] – perhaps because such effects are easier to quantify and/or predict. There has also been preference for quantitative analysis over more qualitative approaches which – while fewer in number – do exist (see e.g. Andersson *et al* [362]). This is understandable as LCIA is ordinarily being used as part of a quantitative *analytical* tool, developed with a heavy emphasis on use in comparison studies. Such undue emphasis on quantification, to the exclusion of qualitative measures will however lead to problems: there will be a tendency to consider quantifiable impacts as more important than that which evades analysis and is therefore not part of the impact assessment model.

The TQM idiom of 'what gets measured gets managed' is particularly relevant here since the converse – of 'what is not measured or modelled runs the risk of being ignored' – is also the case. Any impact assessment methodology *is* a model and considerable effort has gone into the various methodologies in an attempt to form a model which is *representative*. It is critical to remember that *by design* a model is incomplete and it is important to understand what has been omitted - deliberately or otherwise.

What is important – in the context of this thesis – is that impact criteria are related to resources, and there is a placeholder in the assessment for the many resources critical to life support that resist measurement [363] (and therefore do not feature in typical quantitative impact assessment methodologies). This includes resources such as nutrient cycles or the process of pollination (as was discussed earlier from page 46 onwards) – and 'life support functions' using LCIA language [364]. Thus, even though ISO 14042 requires that a choice of impact criteria consistent with the goal of the study be made [365] – and a broad category list would be desirable for sustainable systems – no choice could ever be complete: there are resources critical to life that simply cannot be quantified, and processes that have yet to be discovered. It is therefore fundamentally important to bear in mind that when using an LCIA methodology, the model will likely overlook certain impacts, especially when the traditional impact list is used. This might be clear to some on the supply side of methodology development, but is not necessarily transparent on the demand side [366] (i.e. those applying/commissioning the methodology in practice).

There has been significant effort to mitigate or at least highlight *subjectivity* in the LCIA process in dealing with what is *in* the model. Yet from the discussion above, it is clear that objectivity is difficult to achieve with critical resources being *outside* the model. Ultimately, this reduces confidence in the conclusions drawn in comparative studies as regards the wider context of sustainability, requiring more careful interpretation of results as is discussed further on page 142. In discussing the need for improving the LCIA framework Barnthouse *et al* point out that[367]:

> "the original purpose of LCA, i.e. to inform decision-makers of issues that can lead to and accelerate overall system *improvements*, was overtaken by the desire in some cases to make overall comparisons,"

Here they highlight the desire for 'winner versus loser' comparison, even though a model cannot – by design – provide an absolute truth. Despite its popular use, LCA when used for comparison, does not necessarily represent the optimum use of the tool from the perspective of addressing the goal of a sustainable system (see page 142) since there is a greater emphasis on hotspot improvement. LCIA is the kernel of life cycle assessment, and LCA *is* the most comprehensive tool available to highlight key issues for a comparative decision [368]. However, Weidema already warns of the dangers of misplaced emphasis of some issues over others [369] and the conclusion must then be drawn that great care is needed in *interpretation* of LCIA results – particularly in 'winner versus loser' studies – since some impacts cannot be measured.

Favourably, there is a new paradigm in LCIA emerging: one that recognises the need for 'areas of protection (AoPs)' or 'Safeguard Subjects' which are essentially groups of endpoints as discussed by Udo de Haes and Lindeijer [370]. Such AoPs are useful because they engage the mind in terms of resources that need to be *protected*, rather than simply seeking to capture targeted environmental concerns such as global warming or acidification. This theme is further explored in Appendix A. A key driver for the endpoint approach however is to support LCA comparison studies by making weighting easier; weighting is a subjective element and an unnecessary one where sustainable systems is used as goal. Note also that while significant effort has already gone toward a consensus on preferred AoPs, any list is still ultimately subjective [371]. A problem of working with *damage* to endpoints is that relative certainty is much reduced as compared with the midpoint approach – see Udo de Haes *et al* [372]. There is certainly much work and constructive debate in this area and this remains ongoing under the UNEP-SETAC Life Cycle Initiative. In reality there is probably a need for both mid and end-point data to enhance certainty and provide focus (in terms of being mindful of resources).

In summary, while LCIA is not yet mature there is a drive toward best practice which is necessary for further standardisation, and delivery of homogeneous results. There remain several issues to be fully debated, but mostly the focus is on the use of detailed LCA for the purposes of comparison. The needs of an impact assessment applied internally to a company striving for sustainable systems have a different emphasis and can avoid some of these concerns. In this thesis, the driver is to maximise the availability of natural capital as a sustainability criterion through the elimination of resource availability infringement (see Figure 8 on page 35). It is not the aim to seek to evaluate and present impact data in a manner that makes life cycle x more comparable with lifecycle y. The context and goal of sustainable systems also means trying to deal with resources and impacts that cannot be readily measured, and this is reflected in the impact approach presented in Part III.

6.6 Interpretation & Improvement Methodology

6.6.1 Interpretation

The final phase of LCA is Interpretation. As has already been discussed on page 103, there has been a move away from explicit improvement assessment in favour of a methodological phase that is used to *interpret* the results of an LCA with respect to the study objective or question. Life cycle improvement is now viewed as an *application* of LCA, not a prerequisite driving force or methodological element. Some improvement methodology does exist within the LCA field however and is considered in the next section.

The purpose of the interpretation phase according to ISO is to [373]:

> "analyse results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA or LCI study and to report the results of the life cycle interpretation in a transparent manner.
>
> Life cycle interpretation is also intended to provide a readily understandable, complete and consistent presentation of the results of an LCA or an LCI study, in accordance with the goal and scope definition of the study."

Heijungs and Kleijn warned (in 2001) that ISO standardisation of interpretation is 'premature' due to the lack of experience with the current framework, and advocate more research in the area [374]. The methodological elements in the ISO standard are described as 'procedural' and they present numerical techniques to help interpret the LCA results, including marginal analysis discussed below.

Interpretation of results, whatever the approach used, is of key importance to reporting on the study objective. Depending on the purpose employed, however, the degree of numerical analysis required may vary. A product comparison – particularly in an external context – will require a greater degree of confidence in the results before making recommendations or conclusions than an LCA employed internally to identify environmental 'hot spots'.

In general, interpretation methodology – like goal definition and scoping – does not inherently promote/antagonise the goal of a sustainable system. It is the actual goal defined, and interpretation of LCIA result with respect to this goal, which will have a telling effect in practice. What is also of particular interest is the generation of any *improvement* options at or before the interpretation phase. In practice, the results, recommendations or conclusions drawn at the interpretation stage, based on impact assessment can either antagonise or promote sustainability. Sub-optimisation may occur if there is over-emphasis on data and issues identified within impact assessment to the exclusion of strategies for dematerialisation and so on (as has been discussed in 6.5 Impact Assessment).

6.6.2 Improvement Methodology

As is discussed on page 103, improvement has been seen as an application of LCA, rather than a part of it. Nevertheless, LCA approaches which do directly aim for environmental improvement include the prospective or 'consequential' LCAs, where the study is specifically carried out to assess improvement by making future orientated 'what if' scenarios (discussed further in chapter 7). Fava reports that while such studies are not common, they are on the increase [375]:

> "Comparative studies (within a firm's own product lines) are being completed with the specific purpose of improvement assessment. These comparative studies may range from simple life cycle thinking efforts to complete quantitative LCAs. Is it extensively being done – no; has it been increasing – yes; is there more to do – yes. It is a start"

Comparative LCA being used for improvement assessment is further discussed in the next chapter (see page 142).

While not in the LCA standard, some methodology for generation of improvement options does exist in the LCA literature and may be generally divided into two broad approaches (although both could be used at the same time):

1. A process of analysis or optimisation of the life cycle *per se* in order to support decisions using for example, linear programming (see section 6.6.2.1 below).
2. A more conceptual generation of improvement options by incorporating other tools and approaches such as DfE strategies (see section 6.6.2.2 below and chapter 3).

6.6.2.1 Analytical and Optimisation Approaches for Improvement Options

A fundamentally important point about impact data is that it cannot establish goals for environmental protection [376] and does not itself generate improvement options. Similarly, Robert writes [377]:

> "it is quite complicated to evaluate negative effects in nature, and it is a complicated matter to draw relevant strategic conclusions from data of this kind."

Thus, even if a perfectly *objective* impact assessment were possible, the information would not directly generate understanding of strategic options for potential paths toward sustainable systems or sustainability as a whole. Some opportunities for improvement may be 'obvious' (if subjectively so) and the analysis might help *prioritise* the order in which issues should be addressed.

A number of numerical interpretation techniques have been developed in the life cycle field that help to mitigate this difficulty. The Hanko workshop *Application of Life Cycle Assessments* [378] discussed a conceptual understanding of improvement assessment and available tools – as improvement assessment was still being debated as a step in the ISO guidelines at that time [379]. These tools included *Dominance Analysis (also known as 'Contribution Analysis'* [380]), *Marginal Analysis*, and optimisation techniques such as linear programming.

Both dominance analysis and marginal analysis are useful tools in interpreting life cycle data and directing areas which might attract 'quick-win' improvement. Dominance Analysis is employed to identify 'hot spots' of a life cycle and can be applied with different levels of complexity. Marginal Analysis was presented in the 1992 'Dutch guidelines' on LCA as a means to see how small changes in material flows might have a larger effect within the life cycle as a whole [381]. Heijungs and Kleijn report that marginal analysis was not widely adopted – partly through lack of clarity – and they discuss a more formal version as 'perturbation analysis' in their paper on statistical techniques for potential incorporation in interpretation [382]. They advise that the techniques discussed – including perturbation analysis – are still in their infancy, and thus their usefulness and applicability remains unclear.

Linear programming (LP) as an optimisation tool is discussed in the literature, with applicability in all phases of the LCA [383]. In the interest of improvement, Azapagic and Clift discuss its application to the environmental optimisation of product systems [384]. Bloemhof-Ruwaard, Wassenhove, Gabel and Weaver employ linear programming in a study to optimise recycling rate in a pulp and paper [385]. LP is more powerful than dominance or marginal analysis because it can optimise a large number of variables at once, finding 'solutions' with respect to predefined rules and assumptions. Use of problem-orientated impact data in the LP model – or concentrating on particular emissions such as carbon dioxide – must be used with caution as it predefines improvements in these terms, making the optimisation approach reactionary rather than proactive.

LP – like other multi objective approaches – has the ability to optimise the life cycle with respect to more criteria than simply environmental ones, and can find a range of uses (for example optimal recycling rates – as above). LP can take LCA nearer a decision-*making* tool rather than simply a decision-*support* tool by seeking 'optimal' solutions. In particular with increased awareness of the three domains of sustainability, there have been some documented examples employing economic costs as an objective in the model [386,387]. While this may be attractive to the decision maker there is a danger of moving improvement selection away from, rather than toward, a sustainable outcome. This is because it is vital in the shift towards sustainability that economics actually *reward* sustainable practices and that materials reflect environmental cost in their 'value'. At present this is not the case for we are in a transitional period, moving towards sustainability and towards necessary economic instruments required for its implementation. It would therefore be wise to keep economics and monetary value out of the LCA to highlight preferred options before these economic filters are re-applied for decision making. This will avoid any criticism that the LCA has merely become a BATNEEC or BPEO tool for trade-off.

Going beyond conventional LCA by considering multiple use phases, Mellor, Wright, Clift, Azapagic and Stevens present a model and decision-support framework within which to examine material recovery, recycling and cascaded use [388]. Variables employed in this methodology and the case examples given include environmental insults, economic costs and market value. The use of monetary value is inadvisable for reasons discussed above. Nevertheless, this paper is particularly relevant to the principle of obtaining maximum utility from materials in the socio-economic system (see page 60). Indeed, *utility* is core to the methodology presented in the paper [389]:

> "Central to the CHAMP methodology is the concept of material *utility*. A material at any point in the system is characterised by a set of technical characteristics which determine whether it can be used for any particular process or application."

This section has examined some of the analytical approaches taken to generate improvement options in the LCA field, ranging from sensitivity analysis through linear programming, to dedicated methodologies such as CHAMP. Perhaps unavoidably, analytical approaches tend to be problem-orientated in character (see page 81). Since LCA is still most often used in a retrospective manner [390,391] there is a danger that application of some of these tools may lead to sub-optimisation with respect to sustainability because of the failure to challenge the status quo and a failure to model future scenarios [392]. The use of these techniques in prospective or 'consequential' LCAs where the status quo *is* being challenged will be of greater value in promoting a more sustainable outcome.

A danger of relying wholly on analytical approaches to impact assessment is that improvement can only be couched in terms of quantifiable flows or impacts that are in the life cycle model (see earlier discussion on page 117). Any impacts *outside* the model – for example those that might only be *qualitatively* described such as welfare issues or radionuclide effects – are not going to form part of the analysis or its conclusions. Such numerical interpretation techniques although useful, and indeed essential to some studies, represent essentially 'passive' approaches in the sense that a computer script could be written to carry out these analyses - as is often the case. However, care needs to be taken to ensure that – for a goal of sustainable system or similar – the improvements are made with respect to both problems that are numerically described within the model together with those other problems that may only be qualitatively described such as welfare; nuclear emissions and waste; nutrient cycle interruption etc.

One way in which numerical approaches *can* proactively encourage prevention of resource availability infringement is through dematerialisation of the whole system and through energy efficiency *per se* (see page 49) – thus reducing (in general) all effects, described in the model or otherwise. The 'less is better' approach [393] is sometimes frowned upon as rather simplistic yet it is one of the most direct and effective strategies available. It is particularly important in seeking to mitigate impacts to life supporting natural capital that cannot be numerically accounted for and for which there is no other alternative. As discussed earlier (on page 118), Weidema has expressed concern in terms of relative certainty regarding impacts within the LCIA model in question. Taking this argument further, there is a danger in just tackling known issues in the model – it is important material and energy efficiency *per se*.

Numerical approaches can offer insight into a lifecycle and its interpretation. Yet they do not *generate* improvement options *per se* – this would require the application of strategies such as presented in Part I of this thesis. Since strategies for improvement are the significant agent of change in LCAs for sustainable systems, the generation of improvement options for consideration is critical. Even the prospective LCA requires the selection of choices to be compared in the first place. Sub-optimisation may occur if a sustainable system (or similar) has not been the overriding goal of the LCA. Interpretation with respect to other objectives may lead to interesting and pertinent options being overlooked, particularly if a range of strategies for improvement is not applied. Generation of improvement strategies – for use in both prospective and standalone LCAs – is considered below.

6.6.2.2 Other Improvement Approaches

Within the LCA literature, there are many other approaches to the generation of improvement options that complement the dynamic analysis tools discussed at Hanko. These tend to be more conceptual in nature and may be generally differentiated into those that do or do not explicitly promote sustainability sustainable product design.

Improvement Approaches Not Explicitly Promoting Sustainability

There have been a number of research initiatives aimed at incorporating environmental issues in product development [394]. These programmes include the Scandinavian *NEP* project – discussed below – and the USEPA's *Life Cycle Design* project. While the

USEPA project was not strictly related to LCA methodology. Keoleian and Mereney presented a framework incorporating environmental, performance, cost, legal and cultural aspects in design [395]. The work did not explicitly set sustainability as a goal for life cycle design, but does present valuable direction in terms of strategies for closed and open loop recycling, material and energy efficiency, product life extension and so on. Since most LCAs are retrospective, approaches that start early in product development cycle may put off potential users. Fortunately this situation is beginning to change (see page 103).

Graedel also considers product design through the use of 'LCA in reverse' [396]:

> "to examine the need that the product is designed to fill, to determine the minimal environmental impacts that could be engendered by filling that need, and thereby to design the 'ideal green product' for that purpose."

This is essentially a variant of the prospective/consequential LCA. Graedel is advocating going further than evaluating the consequences of different material or product selection. He appraises alternatives delivering the same function thus concentrating on delivery of service where possible which is a key strategy for sustainability. The example used in the paper is the provision of clean clothing. Graedel starts with an LCA of a conventional washing machine and then performs qualitative comparison of alternatives delivering the same function, including microwave technology for example. Critically, Graedel stresses that it is the functional *system* of providing clean clothes that one wishes to optimise, not just the washing machine. He does however stop short of advocating *sustainable* systems, suggesting that it is:

> "unrealistic to imagine that any product can be manufactured while having absolutely no effect on the environment ... an ideal product is therefore not one that has no environmental impact, but one that satisfies the customer need with the absolute minimum environmental impact".

This appears to be closing the door to environmental excellence on the basis of perhaps 'being realistic'. It is interesting to note that the quality revolution only became possible when total quality was defined as the overriding goal [397]. Accordingly, excellence in environmental performance – or *sustainable* systems – will not become possible until that possibility is consistently pursued.

In later work, Graedel seeks to address the 'modest' attention that interpretation and – in particular – improvement assessment has received [398]:

> "this situation is both curious and unfortunate as performing inventory and impact analyses returns little benefit if those analyses are not followed by actions designed to yield environmental benefits."

Graedel discusses a two stage approach to the improvement stage: first, deriving recommendations from earlier stages and from DfE principles; and secondly prioritisation of these recommendations, according to various criteria including feasibility and economic impact (economic filters, as already been discussed, should be applied last to avoid bias). This is a valuable paper as it discusses improvement methodology explicitly even though – as Graedel himself points out himself – improvement analysis is still in its formative stages [399] (and considered external to LCA methodology as discussed on page 103). In spite of this, Graedel stops short of calling for adoption of sustainability or sustainable outcomes as the goal for LCA studies or improvement options. He writes [400]:

> "the intention is to produce environmental benefits or, at least, minimize environmental harms,"

and therefore he puts environmental improvement in problem terms, rather than in the form of strategic positively stated objectives needed to deliver maximal availability of natural capital critical to sustainability.

Improvement Approaches Explicitly Promoting Sustainability

The Nordic Project for Environmentally Sound Product Development (NEP Project) represented an early effort towards sustainable life cycles through LCA [401]. Product development tools *Quality Function Deployment* and *Life Cycle Cost Analysis* were integrated with LCA [402] for 'sustainable management of product systems' [403]. The NEP method for sustainable product development asserts itself as [404]:

> "one of the most comprehensive methods for Environmentally Sound Product Development "

Hanssen seeks to reconcile the business dilemma through the incorporation of life cycle cost analysis – and he advocates the use of economic parameters as objective functions (such as maximising net profit) rather than as constraints [405]. This is done to help the product development team who have to [406]:

> "take into consideration the system specific conditions, and balance environmental improvements with economy and customer satisfaction".

This approach is an improvement over economics being used as *constraints* in a life cycle model. Nevertheless, it is important to remember that as yet, monetary value does not reflect environmental damage and therefore will introduce unsustainabilities in a model where economics are 'balanced' with environmental improvements. It is becoming increasingly understood that it is the environment, not economics, that represents the active constraint in the pursuit of sustainability – especially where monetary value continues to antagonise rather than encourage sustainable development.

According to this thesis, sustainable systems can only be truly delivered through comprehensive removal of all unsustainable features of the processing route. While this involves tackling the business dilemma (see page 25), there is a need to accept that until the transition to green economics is made, the influence of unsustainable economics as a factor of choice in decision-making is unavoidable. All the more reason therefore for economics to be kept out of the LCA process to highlight possible ways forward unconstrained by unsustainable economic influence. It is important to highlight the available paths to the goal of full sustainability even if the conditions aren't economically viable at the present. At least the option is on the table should the situation change. For example with the onset of landfill tax in Denmark, recycling of construction and demolition waste there has already reached 90% [407]. In the UK the equivalent tax has also had a major impact on some industries.

Strategies for getting to sustainable systems – such as those presented in chapter 3 on page 49 onwards – are key to the identification of options going forward. Hanssen presents four main strategies for the improvement of product systems [408] shown in Figure 33.

1. Reformulating user requirements, to find new innovative solutions beyond the scope of today's product systems.
2. Improvement in the performance of the product system, in relation to user requirements.
3. Substitution of the whole system, or substitution/elimination of parts of the system (subassemblies, components, materials or suppliers).
4. Optimization of the processes and operation of each system unit (raw material acquisition, raw material refining and processing, manufacture, use and maintenance of products, all types of transport, energy production, waste treatment, etc.), or in the interaction between system units (transport, recovery rates of materials, etc.).

From Int. Jour. Cleaner Production, 7, 1999.

Figure 33 - Hanssen's Strategies for Improvement

While beneficial, these strategies are very general and somewhat *ad hoc* compared to the more practical list suggested in chapter 3. On the basis of several case studies, Hanssen concludes that it is not possible to generate a general list of priorities for improvement since each are of different value depending on the context [409]. He further concludes that eco-efficiency in product design does not go far enough:

> "To reach a level of global sustainability, it is not sufficient to improve the eco-efficiency of each product as such. Major changes in the infrastructure for energy production, distribution and consumption, in transport infrastructure systems, and in management of materials in the society is necessary."

Curiously, while Hanssen draws this conclusion, the specific point of considering a future where these infrastructure problems have been rectified – or seeking to challenge such infrastructure - does not appear to feature in the improvement assessment of the case studies discussed. This means that the opportunity to envisage a truly sustainable outcome has been lost. An example of a light fitting study does consider a case of 99%

hydropower during the use phase – but this is made on the basis of current Norwegian energy mix, rather than a specific attempt to model potential *future* scenarios leading to sustainability [410]. There is increasing evidence that some proactive companies are finding innovative ways around the problem of unsustainable infrastructure in their life cycle by bringing operations either physically or influentially under their control (this is further discussed on page 154). This practice can and must be reflected in LCA modelling, as it represents a fundamental feature of the quest for sustainability.

More recent attempts to employ LCA towards sustainability encompass The Natural Step (TNS) [411,412]. The TNS framework is an excellent method of introducing the subject matter of sustainability or sustainable development, particularly the four system conditions for sustainability [413]. It has clear strength in the field of education, yet is weak in application because the four systems conditions – while difficult to fault – are much generalised. It is difficult to visualise their potential implementation (as compared with more practical strategies presented in Part I of the thesis). The task is made worse as the conditions are presented as a series of 'must nots' rather than what must be done, causing further unnecessary confusion (see discussion on page 83).

Attempts to combine TNS with LCA have had mixed success although they have been instrumental in highlighting the need for a more conceptual element in order to fully embrace more sustainable outcomes. Andersson, Eide, Lundqvist, and Mattsson observe that [414]:

> "So far, LCA has been used mainly for comparison and optimisation of existing product systems. Using current production systems as a starting-point can be a drawback; there is a risk that only small improvements can be achieved and that the development of completely new, more sustainable systems is delayed or prevented."

They instead advocate that LCAs toward sustainability could broadly classify systems as being:

> "those heading toward a dead end that would not fit in a sustainable society, transitional systems heading towards sustainability or systems appropriate in a sustainable society".

This is a useful view and is reasonably consistent with the matrix presented by Hanssen (see Figure 26 on page 87).

Robèrt – originator of TNS – himself lauds the potential of LCA to plan ahead [415]:

> "... because we can simulate new conditions for the future, when various things like transport systems, etc. have changed".

Despite the conceptual value of the TNS approach, it has met some resistance from some within the LCA community who are probably more used to LCA as a problem-orientated analytical tool. Upham presents a critique of TNS in LCA [416], which stimulated a debate between Upham and Robèrt in the International Journal of Life Cycle Assessment [417,418]. The debate is illustrative of the opposing views resulting from problem-orientated and conceptual standpoints, including the questions of:

- Certainty versus uncertainty.
- Moving toward a goal versus moving away from adverse environmental impact.
- Quantitative versus qualitative means.

As discussed on page 81, there is a need to encompass both approaches in a toolkit for sustainable systems.

6.7 Conclusions

Life Cycle Assessment methodology can be directly applied to promote sustainable outcomes, but its effectiveness depends on the robustness and appropriateness of the goal employed. Within this constraint, there remain certain aspects of methodology which will also influence the ability of LCA to promote a sustainable system.

Methodological elements of the LCA inventory phase – such as allocation – are quantitative in nature, designed to support its use as a problem-orientated analytical support tool, particularly for comparative LCAs. Complexity of such methodology has undoubtedly lead to interest in 'streamlined' LCA methods to reduce the effort involved in carrying out an LCA. The danger in typical streamlined methods is the removal of the full life cycle view, or other elements critical to identification of improvement with respect to sustainability.

The methodological development of impact assessment has most often been to support a problem-orientated view and decision-support. It does not necessarily follow that this is optimal in directing strategy toward sustainable outcomes. Similarly, the decision to move toward interpretation, instead of a conceptual improvement assessment stage, has helped standardise LCA as a decision-support tool; but simultaneously has perhaps diluted its potential in terms of delivering sustainable systems. In practice, both problem and conceptual approaches are valid and will be required in any serious effort toward sustainability. Some analytical methods such as linear programming have taken the LCA nearer decision-*making* by including the economic dimension; this however risks falling back to a BATNEEC approach. To avoid this, economic mechanisms for *promoting* sustainable outcomes should be sought. Until then, economics is best left out of the fundamental analysis.

Conceptual approaches both within and outwith the direct LCA field have the advantage of being more directive in terms of strategy but at the cost of reduced certainty. Many of these conceptual approaches better promote sustainability than dynamic (numerical) analysis does, in the sense that they often reach beyond optimising individual life cycle elements as they stand and may challenge the system itself. The value of such improvement approaches is in forcing broader thinking in terms of systems - and in innovation in the delivery of those systems. This is quite different from the optimisation of existing products and processes *per se*. There is at least consensus between those applying LCA in problem-orientated and conceptual approaches that LCA used to plan ahead – in modelling future scenarios with sustainable transport infrastructure for example – is an important way forward.

Since methodology is not fully set until the goal or application of LCA has been established, it is important to review how LCAs are actually being deployed in terms of goal, methodology and type – this is done in chapter 7.

Chapter 7 – Review of LCA Approaches

7. Objectives

Sub research question (b) asked:

> **How effective is current LCA methodology in promoting sustainable product systems?**

The primary objective of this chapter is to draw conclusions with respect to this question. A second objective is to identify ways in which LCA methodology and its deployment should be modified, such that in future it better advances knowledge of sustainability and helps deliver sustainable systems. This second objective begins the response to the main research question.

7.1 Introduction

Chapter 6 began forming the answer to sub research question (b) by examining the methodological elements of full detailed LCA. It was established that it is the application of LCA that ultimately defines how the methodology will be deployed, since methodological choices often depend on the goal of the study itself. Clearly, many LCAs may not be explicitly configured to promote sustainable outcomes: it is for the practitioner/sponsor to define the goal. Nevertheless, LCA is increasingly seen as an essential element of achieving broader goals such as sustainability [419] by informing strategy or choice, or delivering 'more sustainable production and consumption' [420]. It is therefore important to gauge its effectiveness to this end.

In order to draw conclusions with respect to sub research question (b) this chapter begins with a general examination of LCA deployment from a general viewpoint and later considers some specific examples to assess how well positioned LCA is to promote sustainable systems. Beginning the response to the main research question for the thesis, the chapter closes with proposed features of a life cycle approach designed to promote sustainability, or more specifically *sustainable systems* (see page 86).

7.2 A General View of LCA

Chapter 6 began by discussing the different ways in which LCA is perceived (see 6.2 on page 105). This is important as it sets expectation for the way in which the LCA will be applied even before the specific goal or question is established and the methodology appropriately configured. In addition, goal setting is perhaps even more critical to the LCA process as it sets the format and nature of the results. For example LCA employed to decide the more eco-efficient of two life cycles has a different format to an LCA employed as hot spot analysis. Appropriate goal definition is critical to the promotion of a sustainable outcome.

7.2.1 Interpretation of Sustainability within the LCA Context

At the international level, LCA is increasingly being seen as a tool to promote sustainable development. The UNEP guide *Life Cycle Assessment: What it is and How to Do it*, states that [421]:

> "the aim of LCA is to suggest more sustainable forms of production and consumption. It uses a scientific approach in which the quantification of effects plays a dominant role".

Given such assertions, it would be valuable if the literature offered more to help the practitioner actually interpret sustainability in an LCA context since the degree to which the pre-requisites for sustainable outcomes are explicitly identified will directly affect the application of LCA to deliver the same. Attempts in the LCA literature to express the merits or needs of sustainability however seem to be limited to balancing the three domains of sustainability – as embodied in the intersecting circles model or the triple bottom line. More often than not, where sustainability or sustainable development is more explicitly acknowledged, it is in general terms only and at best refers to the work of the WCED (the Brundtland report) or the three key themes that form the basis of triple bottom line reporting. For example, the UNEP assertion quoted above seems to rest on a very weak interpretation of sustainability. The guide states that [422]:

> "The ultimate aim of an LCA is to achieve environmental improvement through cleaner production and cleaner consumption, thus contributing to sustainable development"

Sustainability, as described in this thesis – and progress towards it through sustainable development – simply cannot be realised through 'cleaner' or 'greener' measures alone. It requires concrete objectives and the application of strategies towards the achievement of processes and systems *that could go on for ever*. The UNEP follow-up document, *Towards the Global Use of Life Cycle Assessment*, re-asserts the position of LCA in promoting more sustainable outcomes [423], but again does little to interpret what sustainable production or consumption means in general or more particularly what it means in terms of life cycle assessment application or methodology. One of the results of a survey of LCA use, documented within the UNEP report, also reveals that there is not much experience in the use of LCA toward 'design for a sustainable society' [424], underlining the point that business does not yet have an awareness of a roadmap for sustainable outcomes (see page 85).

The EEA's guide to life cycle assessment explicitly asks 'what role for LCA in sustainable development?' Yet despite devoting a whole chapter to the question, there is little interpretation of requirement beyond the triple bottom line [425]. This weak interpretation of sustainability, limited to a need to balance effort among the three sustainability domains as implied by intersecting circles model of sustainability discussed earlier (see page 30 onwards), is rooted in an incomplete understanding of the issues involved. Yet, despite this limitation, there is little doubt that through its holistic perspective and comprehensive nature LCA does inherently *contribute* to sustainable outcomes. CHAINET (see page 85) is illustrative in describing the growing policy acceptance and need of a minimum 4-10 fold improvement in resource efficiency to achieve sustainability [426], thus going further than other life cycle literature in setting out some requirements beyond the triple bottom line.

To empower LCA to its *fullest* in the pursuit of sustainable outcomes, it is surely critical that such an aim be made explicit, and that delivery of an objective like *sustainable systems* as defined in this thesis be the goal of such an LCA. The trouble with this postulate – perhaps inherent to the difficulty in interpretation of sustainability within the

LCA described above – is that an explicit goal of sustainable systems does not really suit LCA in its popular use as an analytical tool since the methodology has been designed for decision-support and goal definition is up to the practitioner/sponsor. This apparent dilemma is explored in the section below.

7.2.2 Supply versus Demand

UNEP, in conjunction with CML, performed a survey of LCA use in 1998, yielding some interesting results. It appears that LCA use on the 'demand side' i.e. in business and policy making is split between the historical development of LCA as analytical decision support tool and its use within a more general conceptual approach [427]. According to the survey:

> "LCA was identified as a scientific/technical tool (as defined by the International Standards Organization (ISO) and the SETAC (Society for Environmental Toxicology and Chemistry) by 13 of the respondents, and as a concept or way of thinking by 11."

Thus while classic LCA *as an analytical tool* appears popular with academics and interested parties on the 'supply side' of LCA, it has not been wholly followed by its adoption on the demand side as a means to assist decision making. This does not perhaps come as a great surprise: the methodology continues to evolve, delivering an increasingly sophisticated and complex analytical tool. Clearly this has advantages and disadvantages depending on the perspective taken, as is summed up by CHAINET (page 77):

> "the general feeling on the demand side is often: 'the simpler the better'; in contrast on the supply side the general feeling is often 'the more detailed the better'".

It is not possible to quantify to what degree supply has failed to meet demand, in the sense that development has perhaps put off potential users. There is however a call from UNEP to tackle 'the absence of a perceived need for LCA' by wider application of a life cycle thinking approach – as opposed to full-blown application of classic LCA – and the development of simpler LCA methods [428,429]. This accompanies a general business need for effective yet simpler, less expensive decision support systems (see pages 89 and 154).

Another finding of the UNEP survey was that environmental improvements tended to be rather modest in scale, and further that [430]:

> "rarely do 'radical changes in product life cycle' occur … and no 'shift from product to service' was mentioned"

From the point of view that radical changes do need to be made (or at least modelled) in order to achieve or plan for maximum availability of natural capital as required by this thesis, this lack of proactive management is a concern. Moreover, industry itself recognises that current rates of environmental 'improvement' are meagre (see page 85). Beyond the usual cost constraint, a reason why resulting improvements are modest might be the lack of development of improvement assessment itself. The very use of life cycle assessment as a decision support tool tends to imply that once the decision has been reached, it is itself an improvement. This may then preclude effort to improve the life cycle beyond the ambitions of the decision or formulation. Comparative LCAs, which formed 30% of the total use reported in the UNEP study, well illustrate this point. The focus of the study is often not on improving life cycles *per se*, but on deciding which alternative is better or more eco-efficient – a much more limited objective. Similarly, where a consequential LCA is carried out the improvements are essentially set during choice of the alternative scenarios to be compared, thus care should be taken that the alternatives embody actual improvements with respect to sustainability before the study begins.

Where the practitioner does want to make a formal improvement assessment he may be frustrated by the trend to effectively drop the improvement step from the LCA framework (see page 103), i.e. development was not pursued. However, it could be argued that the removal of improvement assessment from LCA methodology has had the advantage of shaping LCA and better defining its role in general. Standardised by ISO, LCA is well positioned to help support informed decisions with respect to present day matters. Unfortunately, this has deflected LCA from being a tool that could better optimise for sustainability in a strategic sense. It may seem obvious to those on the supply side – principally academics and experts – how life cycle improvements can/should be made with respect to sustainability. Yet it is not always obvious to those on the demand side where they stand and what needs to be done in order to be more sustainable (see page 85). To remedy this, promoting sustainable systems will necessarily involve goal-orientated and other conceptual elements in LCA, incorporating feed forward strategies for improvement. Immediate options to achieve this would appear to include:

1. The explicit inclusion of strategies for achieving sustainability within the LCA context; and/or where classic LCA is used by itself.
2. Ensuring that practitioners are aware that strategies to maximise the availability of natural resources must be considered as well (see section 3.6 Maximising the Availability of Natural Capital). Most useful in the literature in this regard is probably DfE.

The second option in itself makes good sense and is consistent with the idea of a toolkit presented in this thesis and elsewhere. Indeed, it would be highly desirable if the ISO standards, LCA guides and teaching included such strategies as a 'best practice'. The first of the options appears less attractive for the classic LCA as it would seem inappropriate to force a more conceptual element into a standardised problem-orientated decision support tool. Moreover it would mean overturning a consensus decision to *remove* improvement methodology from LCA in the first place (which was presumably intended to preserve user defined flexibility).

Another possibility would be to develop the more conceptual side of life cycle assessment or a life cycle 'approach' to include improvement capabilities and actually create an LCA approach specifically configured to guide the achievement of sustainable systems. Were this direction taken, it would present an opportunity to meet the UNEP call for simpler approaches to suit the business need for more readily adoptable decision support tools (see page 89). Most importantly, taken to its full potential and developed to deliver sustainable systems, such an approach could also satisfy business calls for a roadmap for sustainable development (see page 85) and address the dilemma described earlier (see page 137). Prerequisites for such an approach are discussed later (in section

7.4.4, page 157 onwards).

7.3 The Various LCA Approaches

The UNEP guide *Life Cycle Assessment* discusses different applications of LCA in the private sector (including product development, marketing and strategic planning) and in the public sector (including policy making, labelling and green procurement) [431]. Across these different applications, it is possible to observe different general styles of LCA construction. This section will take examples of LCA construction to assess the degree to which typical styles might support sustainable outcomes – or more particularly *sustainable systems*. Note that conclusions of these example studies are not reviewed here – more the usefulness of the approach in the promotion of sustainable systems in general.

Study goals are intimately related to the purpose of a given LCA application. For example, application of LCA as hotspot analysis is likely to have a different goal than a comparative LCA being used for marketing purposes. The combination of goal and application puts an LCA in context and effects the methodological approach. High level methodological choices might include streamlined methodology (see page 108) or a prospective versus retrospective approach; lower level choices may for example include the need for specific rather than generic data.

The goal chosen during LCA goal definition and scoping is intended to target the focus on the life cycles(s) of interest. While a sponsor is likely to influence goal setting of an external study, the practitioner should derive the correct specifications of the goal. The practitioner will also select the boundaries, allocation rules, impact assessment methodology and other corresponding methodological choices which will further refine the frame of the study, and which ultimately effect the conclusions. Awareness of sustainability requirements in the goal definition stage of the LCA is therefore critical if the conclusions from the assessment are to advance a more sustainable outcome. The practitioner should therefore work in partnership with the sponsor in all stages, such that the important aspect of 'ownership' in the outcome is addressed.

Some studies seek to promote sustainability explicitly and will be bounded by the definition or understanding that is used/implied. Others studies do not promote sustainability explicitly but instead seek eco-efficiency or merely to perform a benchmark.

While there is a broad spectrum of different ways in which LCAs are applied (see the EEA's LCA guide for example [432]), there are common themes reported in the literature and these are captured below. Different categories of LCA can be observed as follows:

- LCAs explicitly promoting sustainable outcomes
- Comparative LCAs
- Stand Alone LCAs (including hot-spot analysis)
- Targeted Issue LCAs

In practice combinations of these styles are often used as there is a broad continuum of applications, goals and methodological choices. The above list of LCA categories is used to facilitate the discussion over the following pages.

7.3.1 LCAs Explicitly Promoting Sustainable Outcomes

LCAs that explicitly put a sustainable outcome as the raison d'etre of the study, place the LCA in a good position from the outset. However, where LCA has been used to explicitly promote sustainable outcomes, there is failure to define the characteristics of what that sustainable outcome is – see 'sustainable product design' (SPD) for example [433]. The assumption – explicitly stated in the case of the SPD example – is that through a Triple Bottom Line (TBL) approach, the tool contributes directly towards sustainable development. While this may be so, application of LCA to this end is undermined by a failure to define a sustainable or desired outcome (although a TBL-based study including a social welfare dimension must be welcomed). TBL and eco-efficiency approaches‡‡ are weak interpretations of sustainability, falling significantly

‡‡ Consideration of the environment, economic, and social domains is core to any discussion of sustainability. In spite of this – as had already been discussed on page 123 - the economic frame is best applied outside the LCA, so that preferred options for

short of the sustainable systems and processes that must be secured to deliver the ultimate goal. A goal of sustainable systems requires that, at the least, these systems could go on forever or better still, aim to have a 'positive' impact on availability of natural capital.

LCAs explicitly aiming to deliver a sustainable outcome *as described in this thesis* are not as yet apparent in the literature. The Natural Step (TNS) approach (discussed on page 130) probably comes the closest and certainly has the potential to deliver more useful results than a study using the more widespread triple bottom line (TBL) and/or common eco-efficiency approaches. The value of the results of LCA is a function of the strength of the goal employed and the method used. Interpretation of sustainability or sustainable development by key parties in the LCA field has been weak, and TNS, while useful as conceptual strategy, suffers because it lacks a clearly defined goal.

In summary, LCAs tailored for a sustainable outcome from the outset are a welcome development but are thus far are weakened by a failure to define what 'sustainable' means, or at least define it in a satisfactory manner.

7.3.2 Comparative LCAs

LCA has long found popular application as an analytical approach for comparing different products or scenarios. Comparative LCAs can however end up being little more than comparison of the same problems, especially where distinction between foreground and background is not made. Finnveden and Ekvall examine the usefulness of LCA in comparative mode and make criticism of inappropriately narrow goal setting [434]. From the perspective of delivering sustainable systems, there are further concerns where LCA is used to compare product/scenario *x* versus *y*. Formal improvement assessment is often precluded by an assumption that the decision as to 'which is better' represents an improvement in itself. Secondly, the selection of the scenarios used may be *ad hoc* and preclude consideration of an even better option, perhaps incorporating both scenarios, while the matter of long-term sustainability of either life cycle remains

improvement can be highlighted in the absence of *unsustainable* economic influence. Economic sustainability is achieved through finding instruments that support environmental and socially responsible outcomes, not by trade-off.

unchallenged. With so many resources critical to life support being immeasurable (see page 117), the fundamental question would be 'how far is this system from being sustainable, and how can we *make* it sustainable (if that is possible)?' This would be more appropriate in many circumstances, since – as Finnveden and Ekvall point out – while LCA is best placed to minimise the problems in a comparison by identifying key issues for the decision, it is unlikely that a firm decision can be made based on the LCA results alone [435].

In paper making there is an apparent move away from the 'recycling versus incineration' types of comparison, possibly because of the kind of controversy they cause. Perhaps more significantly, as the field has matured there is a realisation that – in this example at least – such a formulation makes an assumption about how waste paper should be handled *before* the study, rather than examining a paper cycle as a whole and then reaching a conclusion about the life cycle itself. This change in approach concentrates on questions like 'what is the optimum recycling rate' (see the example on page 123); or seeks to examine the *utility* of a given material within a system as is done within the CHAMP methodology (see page 123).

Lessons may have been learned from the early recycle versus dispose/incinerate LCAs, but the potential for comparative goal setting malaise finds new forms. For example, Nicolay makes a comparison of petroleum, electric and hybrid vehicles up to and including a moving vehicle but ignores problems associated with transport *use* [436]. Traffic congestion is a major unsustainability – in terms of welfare at the least. A far more valuable study could have looked at options for providing the *service* of transport, which may or may not have included the options examined. Understandably, it is easy to target individual LCAs with such criticism and the practitioners of individual studies may have no choice if they do not wish do lose the sponsor and their interest. The point is that there needs to be greater awareness of both sustainability in itself *and* in goal setting in LCA if its used is to live up to the acclaimed position of a tool that contributes directly to sustainable development.

Comparative LCA finds increased coverage in the literature as the 'consequential LCA' where the consequences of a potential decision are examined with respect to a baseline. This is essentially LCA being used as an improvement assessment tool (see page 121).

Whereas most LCAs are retrospective in nature, this is a prospective LCA, i.e. one that looks into the future (although normally compared to the current situation as a baseline [437]). Prospective LCAs are core to the delivery of sustainable outcomes, since there is a need to model strategies for improvement. In a consequential LCA – where different scenarios or changes to flows are examined – goal awareness is fundamental: key ways forward might remain unexamined if they have not been included in the options scenario in the first place. In the case of a study that examines different options for one aspect of a given life cycle, such as waste management, the sustainability of the whole life cycle may itself go unquestioned. Nevertheless, consequential LCAs are a step in the right direction and are likely to find increasing use when deployed within a business context (considered in the next section).

In summary, while some practitioners shy away from the 'winner versus loser' style comparative LCAs that have caused so much debate, the use of comparative LCA would benefit from greater awareness of sustainability in goal setting in particular. It is also critical that the scenarios considered *challenge* established processes and established thinking if the results are to promote sustainability. Without questioning the intended *function* of the system *per se* and examining improvement options for such things as the supporting infrastructure, a comparative LCA may be a huge effort with trivial reward as far as sustainability is concerned.

7.3.3 Stand Alone LCAs

LCA is most popularly commissioned by business itself as opposed to governments or NGOs. Frankl and Rubik observe that the private sector commissions by far the most LCAs in Switzerland, Germany, Sweden and Italy [438]. Frankl and Rubik also observe that the most popular applications of LCA across a range of different types are 'bottleneck identification' studies and studies used to inform or educate consumers and/or stakeholders [439]. Both of these applications of LCA do not necessarily involve comparative elements, hence their being referred to here as 'stand alone' LCAs.

Bottleneck identification – also referred to in the literature and in this thesis as 'hot-spot analysis' – is most useful when employed 'in-house', since specific process information can be directly employed with potentially more valuable results. This view is shared elsewhere: Graedel argues that from a purely practical point of view, formal improvement assessment methods are [440]:

> "probably most useful primarily within the organisation whose operations are under assessment".

While LCA would in future ideally be incorporated within company management, at an early stage in product development [441], there is a need to accept that for many companies – particularly SMEs – existing products are already mature. Thus there is a need to integrate a life cycle approach into ongoing day-to-day operational management and information systems wherever possible. This could be done by integrating LCA with an EMS and there is already some evidence that a positive relationship can exist between the two in practice [442].

It is also important to note that LCA take up by SMEs is very poor [443] (see discussion from page 155 onwards).

The results of the survey discussed by Frankl and Rubik suggest a strong use of LCA as a management tool within the private sector. Yet in general its use remains uncommon as Heiskanen records [444]:

> "LCA is not as yet a routine, everyday practice throughout industries – and some authors doubt whether it will become that in the future."

Karlson also discusses the need to integrate LCA within in-house management, even though it is [445]

> "mostly not implemented in normal operational procedures".

Results of the study by Frankl and Rubik show that the role of LCA changes over time as the institutionalisation process happens within a company. Initially it tends to be used as an educational tool as the company familiarises itself with the concept in general. This initial foray into LCA is retrospective, but gradually it tends to change to a more prospective and specific use in time. Provided of course that the experience of LCA was perceived as a beneficial one in the first place. Thus a stand alone retrospective LCA is a likely first application in a company, leading to adoption of more goal-orientated and/or sophisticated approaches later.

From the perspective of approaching sustainable systems, the LCA undertaken from within a company represents the optimum application since the company has ownership and can itself make decisions over implementation of improvements. A good awareness of sustainability is of course fundamental to the effectiveness of improvements made and advantage gained. Business will often find that some life cycle improvements require change to infrastructures outwith their direct operational control. Hanssen concludes [446]:

> " ... it is possible to improve product systems significantly by modifications in the product systems which are under the control of the producing company ... radical improvements are only possible to obtain through large changes in the infrastructure in the society, concerning energy production and distribution, closing of material cycles through recovery and use of recovered materials".

While Hanssen is correct that radical improvements are only possible by change to infrastructure, this does not necessarily place such change outwith the influence of the company. There are examples of proactive companies pulling operations under their direct control or influence to promote a more sustainable system as a whole – see the later discussion of the Body Shop (page 154). A further example is set by the carpet manufacturer Interface who manufactures a material and energy efficient carpet in an essentially closed-loop fashion, by leasing tiles and having clever processes in remanufacture [447]. The lease model allows Interface to avoid any problems associated with relying on external companies or infrastructure for recycled or similar materials.

As was discussed earlier (page 63), there is a need to be aware of a transition period where the effects of unsustainable infrastructures have to be addressed. This serves to highlight the opportunity seen by companies such as the Body Shop and Interface to be proactive and stay well ahead of legislation, landfill taxes and so on by adapting their situation so that they *can* influence such infrastructure and the wider life cycle system initially beyond their immediate control. Progress is however hampered by the business dilemma (see page 25) and the perceived need for economic pragmatism, but there are at least two ways in which LCA can be employed to mitigate this:

1. As has been discussed, to find ways that the company can influence processes outwith its normal control.
2. To ensure that possible improvement options are recorded or modelled in an improvement assessment. This means that possibilities *not implemented* are 'on the record' and available to implement when future economic and potential infrastructure changes become more favourable.

In summary, the stand alone or 'in house' LCA represents the best opportunity to put sustainable systems – as an operational goal – into practice since *system-specific* information will be available and the sponsor can act directly on results. There is a need to ensure that infrastructure effects are examined and challenged, rather than dismissed as external to the company.

7.3.4 Targeted Issue

LCAs are sometimes carried out which target a particular concern such as recycling or, more commonly, a particular environmental issue such as global warming [448,449]. These LCAs are in danger of missing the point of taking a life cycle perspective in the first place by singling out a particular life cycle element, instead of examining the life cycle system as a whole, which will include the concern being address within the wider context. Better awareness of sustainability in goal setting is instrumental here because such targeted LCAs may in fact antagonise effort towards sustainability, since they overlook opportunity to challenge or examine the whole system in favour of looking at only one area of it. This type of LCA may be done for compliance or similar purposes, but it introduces a high level of subjectivity and unnecessary restriction before the study is even begun. Many of these criticisms are also true of streamlined LCA approaches that selectively ignore different parts of a given life cycle.

In summary, targeted issue LCAs must largely be discouraged. What gets measured gets managed; what goes unmeasured gets ignored and is unavailable for improvement assessment with respect to any sustainability criteria.

7.3.5 Discussion

The above discussion of the different approaches to LCA configuration and deployment has examined common 'styles' of LCA in their applicability to the promotion of sustainable systems. Two viewpoints are useful in appraising these approaches towards sustainable systems, the methodological and practicable:

1. From the *methodological* point of view, the LCA which explicitly seeks to embrace sustainability has the potential to go the farthest in its achieving it. The comparative and stand-alone LCAs will deliver results within the context of the formulation, decision or goal used at their inception. The ability of such LCAs to promote sustainability will likely have a great deal to do with the awareness of sustainability as applied at the time of goal setting. The default position of eco-efficiency is likely to inherently promote a sustainable outcome environmentally speaking, albeit from a sub-optimal viewpoint. Of all the approaches studied, it is 'targeted issue' LCAs that are most likely to frustrate a more fundamental move towards sustainability; by taking too narrow a view, they fail to make the best of taking a life cycle perspective in the first place.
2. From the *practicable* point of view, the in-house LCA – irrespective of its stand-alone or comparative mode – is perhaps the most likely to have the greatest effect *on the ground*, i.e. in the sense that decisions are taken and improvements with respect to sustainable systems are directly implemented.

An important conclusion therefore is that an LCA employing an explicit goal of sustainable systems, used as an internal management tool, has the maximum potential to *deliver* sustainable systems. This will be expanded upon in Part III of this thesis.

7.4 Maximising the Potential of LCA Towards Sustainability

LCA methodology has largely been developed from a problem-orientated outlook as Frankl writes [450]:

“The development of the tool LCA is an answer to the challenge of environmental pollution and deterioration. The challenge is nowadays a task for the whole society and all the actors have to look to find their contribution to pathways to sustainable development.”

As an analytical decision support tool its ongoing development has led to sophisticated methodology well suited to addressing problems, questions and comparisons. Yet it does not necessarily follow that development of LCA means that it is optimised to promote sustainable systems or sustainability in general. Indeed, the history of its development brings both advantages and drawbacks from the perspective of re-orientating its use as a more strategic tool aimed at progressing towards a truly sustainability society. As a result it would be highly advantageous to seek to identify ways to capitalise on the advantages of, and minimising any downsides in, the methodology and its use for sustainability.

This section considers strengths and weakness of LCA as a component in a toolkit for the achievement of sustainable systems by drawing on relevant literature and knowledge gained in this review. To facilitate this the following three criteria for a successful toolkit for sustainable systems are used (see page 87):

1. a goal of sustainable systems (with its implications)
2. a systems perspective
3. a ready applicability

The above criteria are used to structure the discussion that follows – which closes with the proposed features of a life cycle approach designed to promote sustainability, or more specifically, to promote sustainable systems.

7.4.1 Goal Based on Sustainable Systems (with its Implications)

Earlier in this chapter, it was highlighted that LCA is seen by some as an instrument for supporting sustainable development and moreover that this view has been adopted at the international policy level. The actual interpretation of what sustainable development means and – in particular – how and to what degree LCA can contribute to a sustainable future has already been highlighted as rather weak. Indeed, there seems to be little interpretation of sustainability beyond the triple bottom line approach. It also seems that LCA is thought to *directly* contribute to sustainable development simply through its life cycle perspective or through encouraging eco-efficiency. If so, this would be an unwise assumption.

In order to realise the full potential of LCA as a tool to aid the delivery of sustainability and to reduce some of the vagueness of the TBL and eco-efficiency approaches there is a need for an explicit pertinent goal to be included. Sustainability as a whole is too broad an aim for LCA alone or any other single tool. LCA must be backed up by a framework offered – in part at least – by a toolkit such as described in Part I and being assembled through initiatives such as CHAINET. This is especially important when dealing with the complex scenarios of the transition from present systems to sustainable ones. The goal of sustainability may be operationalised within LCA by adopting an explicit goal of *sustainable systems* however. Both the system that delivers products and services to the consumer *and* the products themselves needs to be sustainable – not merely the system output. LCA is already employed to analyse environmental impact on the basis of *function*, rather than a material product itself. If awareness can be expanded from the seeking of eco-efficient products – or product function – to the delivery of efficient and *sustainable* systems themselves, then the true potential of the life cycle approach can be realised.

Rather than using classical problem-orientated LCA methodology – which seeks to be flexible and user defined – it has already been proposed in this thesis (see page 139) that a life cycle *approach* developed explicitly to promote sustainable systems could be used. This would allow the dilemma discussed earlier (on page 137) to be avoided. In cases where an explicit goal of a sustainable outcome is not specified within LCA, there is still a need for a better awareness of the consequences of goal definition. Criticism has been made of inappropriately narrow LCA goal setting [451] elsewhere in the literature and this criticism is especially important from the perspective of delivering sustainable systems. Since LCA is celebrated for its holistic perspective, it would be a major missed opportunity for sustainable development if LCA studies are weakened through goals which are too narrow or too targeted.

Central to the premise of sustainable systems is that they should contribute toward achieving the goal of sustainability. Sustainable systems as a goal to work toward – or 'backcast from' to use TNS language – requires both feed-forward strategy and feedback trim, employing the process control analogy. A clear advantage of LCA as it stands is that it can offer a framework within which to generate strategies for the achievement of sustainable systems and to appraise any improvements made towards this goal. If sustainable systems are to be achieved, it is also important that an improvement assessment is explicitly carried out with respect to the goal in a systematic way. General strategies for achieving the goal of sustainability were presented in Part I, and this represents the feed-forward elements of the approach to be used. A more formalised and systematic feed-forward structure, incorporating a working definition of sustainable systems is still required however, so that the achievement of the goal may be operationalised. Where improvements *are* made, there must be a follow-up exercise to see that the anticipated changes are being accomplished. A key element of LCA employed to deliver sustainable systems is a monitoring procedure to gauge progress. This is the feedback element using the process control model.

While there is a lack of tools that have a significant or main focus on strategic planning [452], LCA is well positioned to offer this kind of assistance when appropriately configured and deployed. Already there is increasing use of prospective LCA where consequences of management decisions can be evaluated [453] and this could be widened to include an assessment with respect to sustainability or sustainable systems.

When applying LCA for sustainable systems there is a need to recognise and acknowledge a transition period before a sustainable society can be fully realised (see page 63). During that time, for example, common infrastructure such as energy and transport will be changing [454]. Within the context of sustainable systems, there is a need to challenge perceived wisdom in how to handle this transition period. For example, it has been observed – on the basis of the life cycle perspective – that photovoltaic panels have a long pay-back time in terms of net carbon dioxide emissions compared to current means of power generation [455]. Making such an assertion however is odd from the perspective of sustainability. First it makes the comparison in purely targeted problems terms (i.e. too narrower a scope) and secondly there is a need to accept that during this transition, unsustainable technology must be used in order to manufacture the sustainable technology required for sustainable systems. The useful observation that can be made is that photovoltaic technology is as yet immature and can add further value when improvements can be found which will reduce the payback time. Location also changes the perspective entirely: solar panels are being used to great advantage in developing countries to power water pumps in locations where more conventional power stations simply do not exist [456] and the electricity grid is unlikely to be sustainably extended. Another example of transition is the need to get recovery and recycling infrastructure in place now to take advantage of recycling technology as soon as it can be developed and scaled up, even though the short term economic gain of such infrastructure is minimal.

Payback time is also a function of the economic reward system in place, which must develop towards promoting the sustainable. In the mean time, it is advantageous that consideration of the economic domain is generally left out of the LCA process since this offers the advantage of being able to highlight optional paths without being effected by unsustainable economics or monetary influence. This allows for a separate process to be brought in where economic instruments can be sought at the same time that promote or support sustainable systems. Here the economic system is set up to reward the sustainable system and therefore enhance economic sustainability. If economics are not part of the solution, they remain key to the problem. Trading off environment against the economic domain, a symptom of the business dilemma discussed earlier (see page 25), does not contribute to sustainability and ultimately is not an option unless there is real environmental choice to be made with no loss to availability of natural capital. In the interim, optimisation with respect to economics remains a major issue and there is an apparent trend in development of LCA for decision-*making* (see page 123), rather than simply as decision-*support*, through the inclusion of economic considerations. This does unfortunately confuse the issue for example by promoting – rather than avoiding – the trade-off of unsustainable monetary value against the environmental domain. Such trade-off is unavoidable for as long as the transition period exists, but as discussed is best left outside the LCA process.

7.4.2 Systems Perspective

Life cycle tools are valuable principally because they put particular environmental concerns into perspective within the life cycle context, mitigating the danger of 'problem shifting' and encouraging corporate responsibility to extend to the entire product life cycle - also known as product stewardship. This holistic perspective is a key first step in the awareness of the issues involved in moving toward sustainable systems. The value of the life cycle perspective cannot be underestimated – it has already been recognised at the international policy level and indeed has permeated western culture [457]. Even outside the classical LCA scope, which some have sought to widen, the life cycle perspective is still key - see earlier discussion of framework for chain analysis by Mellor *et al* (page 123). Most usefully, the holistic nature of LCA and other conceptually related tools can easily be adapted to accommodate the widest of perspectives demanded by sustainability. This can be done by seeking *global* natural capital and welfare for example rather than simply seeking to improve the life cycle in question.

LCA lends itself well to the study of systems, which is one of its defining features, yet the focus tends to remain on delivering the product or product function in the most eco-efficient way. This is where the value of the life cycle perspective is perhaps *overestimated* – in that it somehow is taken to imply sustainable development through its very use. The goal of sustainable systems also requires that the whole system should be sustainable which inherently includes the product (or service) in use as well as the product system itself. LCA provides, for example, an excellent framework within which to apply DfE principles. However principles such as 'design for disassembly' tend to centre on the product itself and not on the whole system. Even the concept of 'sustainable products' represents an incorrect focus as sustainability demands a much wider focus on systems [458] or groups of systems, for example at the corporate level – that deliver *function*, the result of which may or may not be a consumable product. The whole system, from cradle-to-grave should in essence be sustainable. It is possible that both product and system perspectives lead to the same improvements in a given situation, but the distinction is a fundamental one and must be made.

The life cycle approach does reduce the potential for problem shifting however and puts new perspectives on the problems themselves. In addition, the goal of sustainable systems will widen this perspective further and it is important that LCAs are used to *support* rather than to *make* decisions about results of the life cycle model. Interpretation of results and improvement assessment with respect to the goal of sustainable systems is critical here since some options may not be obvious. It is therefore prudent to model future scenarios where cleaner and/or sustainable energy is available, for example. Consider, for example, transport distance being a deciding factor over whether or not to use recyclable packaging [459]. Here there is a need to illustrate that it is transport that is the problem – not necessarily the packaging. Modelling the influence of more sustainable forms of transport on the decision within LCA has been suggested and would be useful in these situations [460,461]. Thus the decision may still be whether to implement scenario *x* over *y*, but at the least it is on record that *y* is the more sustainable when power is cleanly generated, or where transport itself is sustainable.

It must be remembered that without improvement action, an LCA study remains just a report. Without implementation of preferred improvements with respect to sustainable systems, little progress can be made. It is also worth remembering that some key gains in improvement of the life cycle with respect to sustainability can be found *outside* the direct influence of the sponsor. Hanssen observes that more radical improvements involving a change in infrastructure are difficult [462,463] because it is in the 'background' of the life cycle, and therefore outwith the operational control of the study sponsor. Yet despite this, visionary companies such as The Body Shop are already tackling this matter head on by pulling unsustainable processes that are outwith control *within* their operation. Before it was possible to choose electricity supplier in the UK, The Body Shop bought a 15% stake in a wind farm to offset the electricity used in its UK factory [464]. Since competition has been introduced in the electricity market, The Body Shop has changed energy carrier to Ecotricity (electricity supplier of renewably generated power) to supply all its shops in the UK [465]. This is taking a firm and proactive step toward sustainable systems.

7.4.3 Ready Applicability

LCA is already a popular tool employed in environmental decision-making [466] and because of ISO standardisation it is likely to retain this position. The methodology continues to evolve, delivering an increasingly sophisticated analytical tool. However, strengths of LCA achieved through its level of sophistication are its 'Achilles Heal'. Weidema observes [467]:

> "The simplicity and ease of applying LCA as a qualitative technique has lead to an undue academic interest in the problems that occur when the technique is applied in its quantitative form. Thus, LCA is too often presented and perceived as an excessively quantitative technique at the expense of the many results obtained from qualitative studies."

Academic development of LCA methodology outstrips practice as may be expected (see earlier discussion on page 137), but there is concern that potential users are being put off LCA altogether for a number of reasons ultimately related to its level of sophistication including [468,469,470,471]:

- Expense in terms of total cost of ownership (resource and time intensiveness, including time needed for education).
- Need for expert input.
- Data intensity.
- Complexity.

Such problems are also recorded by UNEP [472]:

> "The lack of expertise for performing and understanding LCAs is a particular problem in developing countries, as well as for Small and Medium-sized Enterprises (SMEs) and policy-makers. Communication about the LCA methodology and the LCA outcome is also a problem. The complexity of the LCA model often makes decision-makers lose sight of the overall picture because they cannot follow how the outcomes are reached and what the implications of some of the choices are".

And most recently within electronic industry press [473]:

> "while many large companies undertake life cycle assessments in order to save money through reducing material and energy inputs to their

processes and save on energy and disposal costs, many SMEs are reluctant to undertake the assessment due to the high financial and time costs".

Most LCA development and standardisation has moved toward a detailed LCA process [474]. It would be a disservice to the classic LCA tool to remove the more complex elements that cause some of the criticism summarised above. Not the least of which because it would mean losing some of the elements that make it such a useful analytical tool. It is however such concerns that have encouraged development of 'streamlined' LCA, discussed in chapter 6, as Todd *et al* observe [475]:

> "A continuing concern ... is the cost and time required for LCA. Some have questioned whether the LCA community has established a methodology that is, in fact, beyond the reach of most potential users. Others have questioned the relevance of LCA to the actual decisions that these potential users must make. These concerns have encouraged some practitioners to investigate the possibility of 'streamlining' LCA to make it more feasible and more immediately relevant without losing the key features of a life-cycle approach"

Chapter 6 urged caution in the use of streamlined methods that focus purely on targeted issues (see page 108). Such approaches may overlook the opportunity to reduce the impact on availability of natural capital across the whole system. These problems arise particularly where less than the full life cycle view is taken. Where steps are taken to try increase the adoptability of LCA as a tool through streamlining, it is important that the analysis does not ignore the very issues that frustrate the delivery of sustainable systems.

If classic LCA is putting off potential users, yet existing streamlined methods are unsuitable in the pursuit of sustainable outcomes, there remains a need for a simple and easily understood, but not simplistic life cycle approach as called for by UNEP (see page 137). Such an approach is of great value in determining simple, prescriptive strategies which will engage businesses in practical environmental improvement, no matter how 'obvious' such strategies may seem to some [476]. This need is one of the themes explored in section 7.4.4 below. In terms of engaging business, LCA can also be used in identifying cost savings, for inefficiencies can often be revealed through performing an LCA and any resulting savings could offset the cost of the LCA itself. The promotional value of LCA-derived information to companies can also be very considerable, particularly where improvements can be demonstrated and communicated.

7.4.4 Features of a Complementary Approach

It has already been argued that it would be inappropriate to force the goal of sustainability explicitly into classic LCA methodology, since goal definition is left to the practitioner and improvement is now seen as an application of LCA (see page 103). Moreover, making LCA 'more adoptable' by reducing some of its sophistication would be at the cost of reducing elements that make it useful as an analytical support tool in the first place.

Two key conclusions are that:

1. There is a need to take care that where classic LCA *is* used, the formulation (e.g. decision) is pertinent to the delivery of sustainability.
2. There remains a need for an LCA method that has sustainable systems as its explicit goal, and also addresses the call for a simpler method than classic LCA represents.

Addressing the second point does not require developing an *alternative* LCA methodology – rather one that complements classic LCA and other tools pertinent to a toolkit for sustainability. This conclusion is not dissimilar to one reached by Karlson [477]:

> "One main road to improve the [cost-benefit] efficiency of the LCA tool is to 'build away' the drawbacks, e.g. through developing databases facilitating access to inventory data .... Another opposite main road is to narrow the scope and develop LCA into an easy to use and resource efficient tool aimed for coarse judgements with the option to conduct more complete assessments when necessary. These two alternatives are

not necessarily in opposition to each other. The best solution would probably be to explore both in parallel."

Karlson does not explore the second option in his thesis (this is one of the conclusions).

LCA methodology applied from a more conceptual angle is not as well documented as classic 'detailed' LCA, perhaps with the exception of existing 'streamlined' LCA approaches which have the drawbacks discussed in chapter 6. Many features of existing streamlined approaches have already been criticised. Care must therefore be taken when developing a complementary method to ensure that it builds on the strengths of LCA without introducing elements that weaken its position to deliver sustainable systems. As it is, loss of some sophistication will inherently introduce a degree of uncertainty. On the basis of the preceding analysis, key features of such a methodology include:

- An explicit goal of sustainable systems (see page 86).
- Being readily adoptable, and avoiding unnecessary complexity so it can be used easily.
- Employing sustainability criteria built on resource availability to form the basis of impact assessment, and of an improvement strategy.
- Encompassing both goal and problem frameworks, i.e. feed-forward and feedback approaches, not just feedback (see page 82).
- An explicit improvement assessment and follow-up after implementation (see page 151).
- Integration with ongoing operational management and information systems of the organisation where appropriate (see page 145).

An LCA-based approach with these features could add further value by providing a framework within which to apply other tools within a toolkit, generating options and ways forward but leaving more complex decision-support to more appropriate tools such as classic LCA or decision analysis. Economic judgement would be deferred to a separate process before any decision making. This has the benefit of identifying both the preferred paths forward and any economic constraints preventing their realisation.

Such an approach is explored and appraised in Part III of this thesis. The significance of more conceptual approaches in widening the appeal of LCA cannot be underestimated. Indeed, the need for development of LCA as a more conceptual approach of 'life cycle management (LCM)' has been recognised under the SETAC / UNEP life cycle initiative [478,479]. LCM remains at the definition stage at present [480].

7.5 Conclusions

Sub research question (b) asks:

> **How effective is current LCA methodology in promoting sustainable product systems?**

The value of the life cycle perspective is recognised at the international policy level. Chapter 6 concluded that Life Cycle Assessment methodology is suitable for direct application in promoting sustainable outcomes. Heavy development of LCA as an analytical decision support tool, including popular use for comparison, has helped carve a niche and resulted in standardisation by ISO.

LCA is also increasingly seen as a tool to promote sustainable development. Since goal definition is left to the practitioner, the effectiveness of a given study in promoting sustainability will be bounded by the definition or understanding of sustainability itself employed at its inception. Unfortunately, attempts to describe sustainability or sustainable development in the LCA literature are often limited to a weak interpretation of balance between the environmental, social and economic domains. Moreover, there is perhaps an assumption that application of LCA implies promoting sustainable development through its very use. Comparative or targeted issue LCAs, aiming to deliver more eco-efficient life cycles illustrate this point. They are useful, but risk a sub-optimal outcome as the focus is not on the delivery of long-term sustainability of the system as a whole.

Sustainability as described in this thesis cannot be delivered by eco-efficiency objectives alone. It requires very clear objectives and the application of strategies towards the delivery of processes and systems that could go on forever. It is not always obvious to those on the 'demand side' of LCA what to do in order for a life cycle to be sustainable. As such, it would be highly desirable if the ISO standards, LCA guides and teaching included general strategies for improvement as a 'best practice'. It is therefore concluded that there is an opportunity to deliver an LCA-based approach with an explicit operational goal of sustainable systems together with supporting, conceptual strategic elements.

Another opportunity for enhancing the strength of LCA in promoting sustainable systems is the accessibility of the tool itself. The detailed LCA configuration has however put off potential users and this is despite business calls to know what to do in order to be more sustainable. The value of a robust yet simpler, less sophisticated method that can attract a wider user base – particularly SMEs – cannot be overstated. Since a pre-defined goal and improvement methodology do not fit the classical detailed LCA scope, this would need to incorporate a modified approach that would complement LCA as part of the wider environmental management toolkit. The features of such an approach, discussed in this chapter, will be configured and appraised in Part III.

Part III - A New Direction for Life Cycle Assessment?

"Would you tell me, please, which way I ought to go from here?"
"That depends a good deal on where you want to get to," said the Cat.
"I don't much care where — " said Alice.
"Then it doesn't matter which way you go, " said the Cat.

Lewis Carol, *Alice's Adventures in Wonderland*, 1865.

Chapter 8 - Life Cycle Assessment Towards Sustainability (LCATS)

8. Objectives

The main research question asked:

> **How should LCA methodology be configured such that it better promotes environmentally sound product systems, and thereby sustainability?**

Chapters 8 and 9 answer the question by developing and appraising a life cycle approach which complements classic LCA as part of a wider toolkit for sustainability. This is an attempt to form a comprehensive approach (in the sense of its objective, impact assessment and strategy) whilst trying to avoid some of the key criticisms of classical LCA discussed previously.

8.1 Terms of Reference for the Approach

8.1.1 Purpose

To draw together a methodology – Life Cycle Assessment Towards Sustainability (LCATS) – tailored for the purpose of a practicable implementation of life cycle assessment with the explicit aim of delivery of sustainable systems.

8.1.2 Drivers

A number of drivers for the creation of a modified life cycle approach have been drawn up in chapters 6 and 7, and discussed in section 7.4 (see page 148). Key features required were summarised on page 158 to include:

- An explicit goal of sustainable systems
- Being readily adoptable, and avoiding unnecessary complexity so it can be used easily
- Employing sustainability criteria built on resource availability to form the basis

of impact assessment, and of an improvement strategy

- Encompassing both goal and problem frameworks, i.e. feed-forward and feedback approaches, not just feedback
- An explicit improvement assessment and follow-up after implementation
- Integration with ongoing operational management and information systems of the organisation where appropriate

8.1.3 Constraints

The LCA approach used here is largely based on LCA as defined by ISO 14040 (and related standards) but with modifications as dictated by the abovementioned needs. The point is to provide a practical methodology for the delivery of sustainable systems compatible with but constrained by the scope of the ISO standards as far as possible.

8.2 Methodology of Life Cycle Assessment Towards Sustainability

8.2.1 Preamble

There remains uncertainty within businesses about what they need to do in order to be sustainable (see page 85). This section presents a methodology called *Life Cycle Assessment Towards Sustainability* or *LCATS*. LCATS is based on LCA, but employs a pre-defined goal of a sustainable system, as defined earlier, and uses strategies to help business move beyond a BATNEEC philosophy towards integrated environmental and economic performance. Since the goal is pre-defined, this essentially forms 'an approach' [481] rather than being classical LCA where the goal is left to the practitioner. The approach is developed to encourage wider uptake of LCA and life cycle thinking in general – particularly by, but not limited to, SMEs. It is intended to be used internally, moving the corporate operation from the current baseline progressively toward a *totally sustainable system* as defined earlier and depicted by the upper dashed line in Figure 34 below.

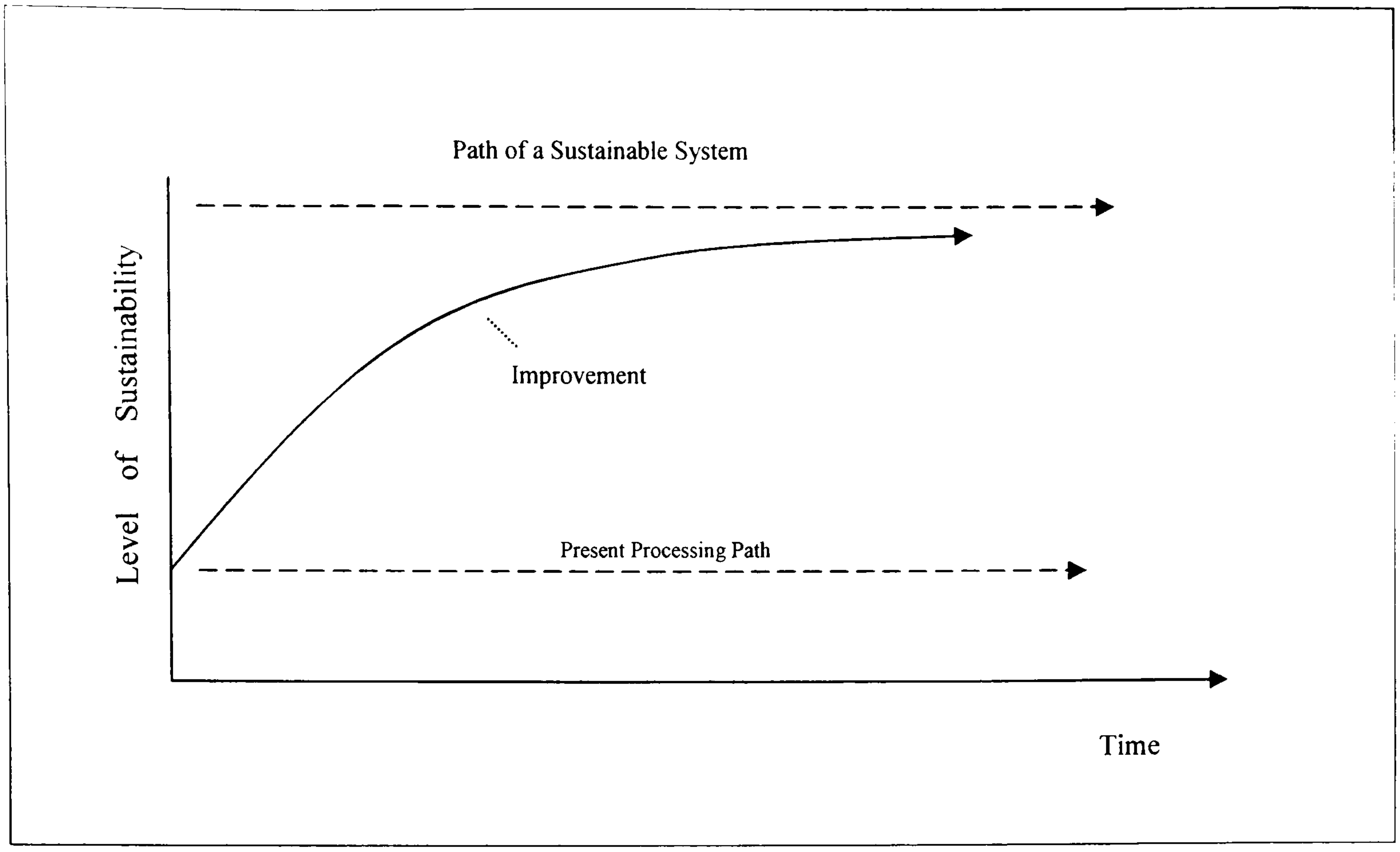


Figure 34 - Approaching Sustainability

This figure describes the movement of a cradle-to-grave processing path from a far from sustainable initial condition towards a final condition, progressively nearer to the sustainable system, which the processing route can support.

8.2.2 Discussion of Methodological Elements

There is a need to integrate the specific drivers for a modified LCA approach in a simple prescriptive methodology that helps business understand, plan for and track progress toward sustainable systems. This necessarily requires:

(a) Describing the goal of sustainable systems in robust, and generally applicable terms

(b) Helping the practitioner understand scope in terms of data collection and boundaries of influence, that is relevant to the business operation (site and business specific)

(c) Carrying out impact assessment in a manner consistent with the goal, but also in a manner that is illustrative of the issues involved and of progress made (this means using some sort of sustainability impact criteria).

(d) Explicitly including an improvement assessment consistent with the goal; one which is prescriptive in terms of conceptual strategy, and practical implementation.

(e) Integration within in-house operational management where possible although this need not be a prerequisite. Provision for an ongoing assessment and the means to follow-up on improvements where implemented is important however to ensure a continuous procedure of analysis and improvement.

8.2.2.1 Robust Goal (a)

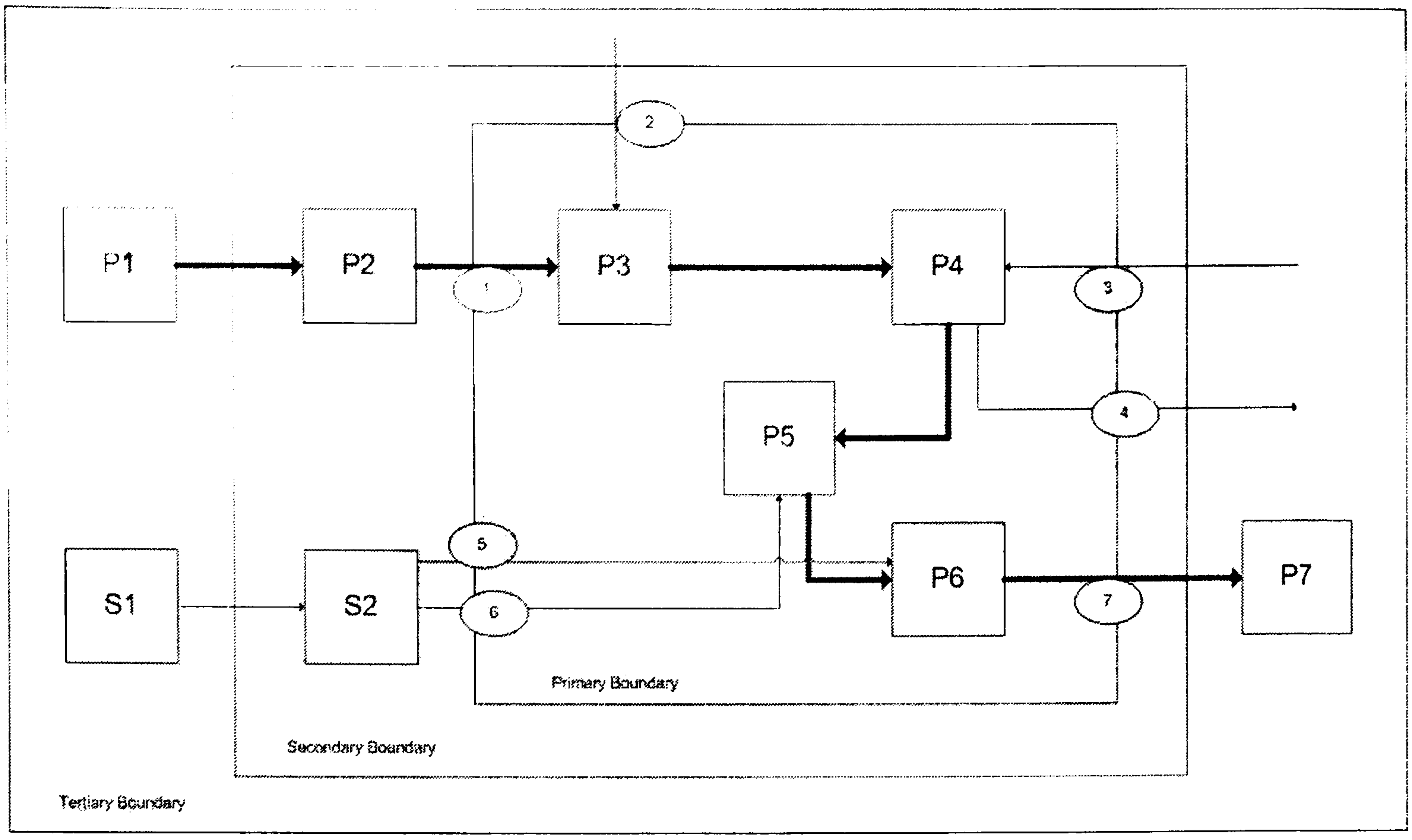
The goal of sustainable systems has already been described in Part I (see page 86).

8.2.2.2 Understanding Scope (b)

Operational control is a key element in the eventual ability of a company to move towards sustainability. In LCATS, three boundaries are defined to reflect different degrees of company influence in the operation from cradle-to-grave. Many contentious issues in boundary setting arise in classical LCA through the methodological needs of comparative studies. Here the focus is on delivering a sustainable system and not comparison and – as a result - any problems related to boundary setting appearing in classical LCA are avoided. The ultimate aim of LCATS is to capture the full life cycle of the system; consider all influences on sustainability of all operations cradle to grave; and use this to direct improvement. The analysis starts with an initial life cycle diagram of the system from cradle-to-grave, with three logical boundaries illustrating varying levels of operational control by the business, i.e. (1) direct, (2) partial and (3) no control (but including possible areas of influence) – see Figure 35. These boundaries will be referred to as primary, secondary and tertiary boundaries respectively.

The 'flow' diagram is constructed in conjunction with the usual mass and energy balance, as championed by chemical engineers (containing inventory information for the system). Note that the primary boundary – direct operational control – will employ process-specific information, while operations outside this boundary may need generic data (this is rather like the distinction of foreground/background systems in classical LCA). The diagram is consolidated as the LCA continues to mature and the data collection effort expands.

It is at this early stage of the LCA that economic influence should also be highlighted and formally removed from LCA data and analysis for it is important to set an unambiguous baseline. Such considerations will figure later when improvements are prioritised in order of economic feasibility, but this is not the fundamental analysis. Rather it is the result of applying particular economic constraints to the systems after assessment of the preferred unconstrained ways forward.



Operational control is a processing/business reality which has a determining effect on the achievement of sustainable systems, cradle to grave. In order to help identify operational control, three boundaries are employed. The diagram illustrates the 3 boundaries of operational control where the *primary* boundary encompasses operations under direct operational control of the company; the *secondary* boundary encompasses processes or ancillary supply outwith direct control, but under some influence of the company, e.g. suppliers; the *tertiary* boundary encompasses elements under no current influence of the company (but within the 'technosphere'); and anything outwith the tertiary boundary is the wider natural environment. The numbered streams 1 to 7 are used to construct the RAIL diagram (see Figure 36). Streams *incoming* to the primary boundary (e.g. stream 1) inherit all upstream environmental insult. Streams *leaving* the operational boundary (e.g. stream 7) inherent all environmental insult downstream of this point. Note that these boundaries help the practitioner/company to visualise and ultimately 'operationalise' Extended Producer Responsibility (as discussed on page 54).

It may be helpful to begin the LCATS study using the primary boundary for a first data-gathering and analysis iteration, then expanding the LCA to include the secondary boundary and so on.

Processes P1, ... Pn and the **thick** line denote the main cradle to grave processes and route.
Processes S1... Sn illustrate supply or ancillary processes

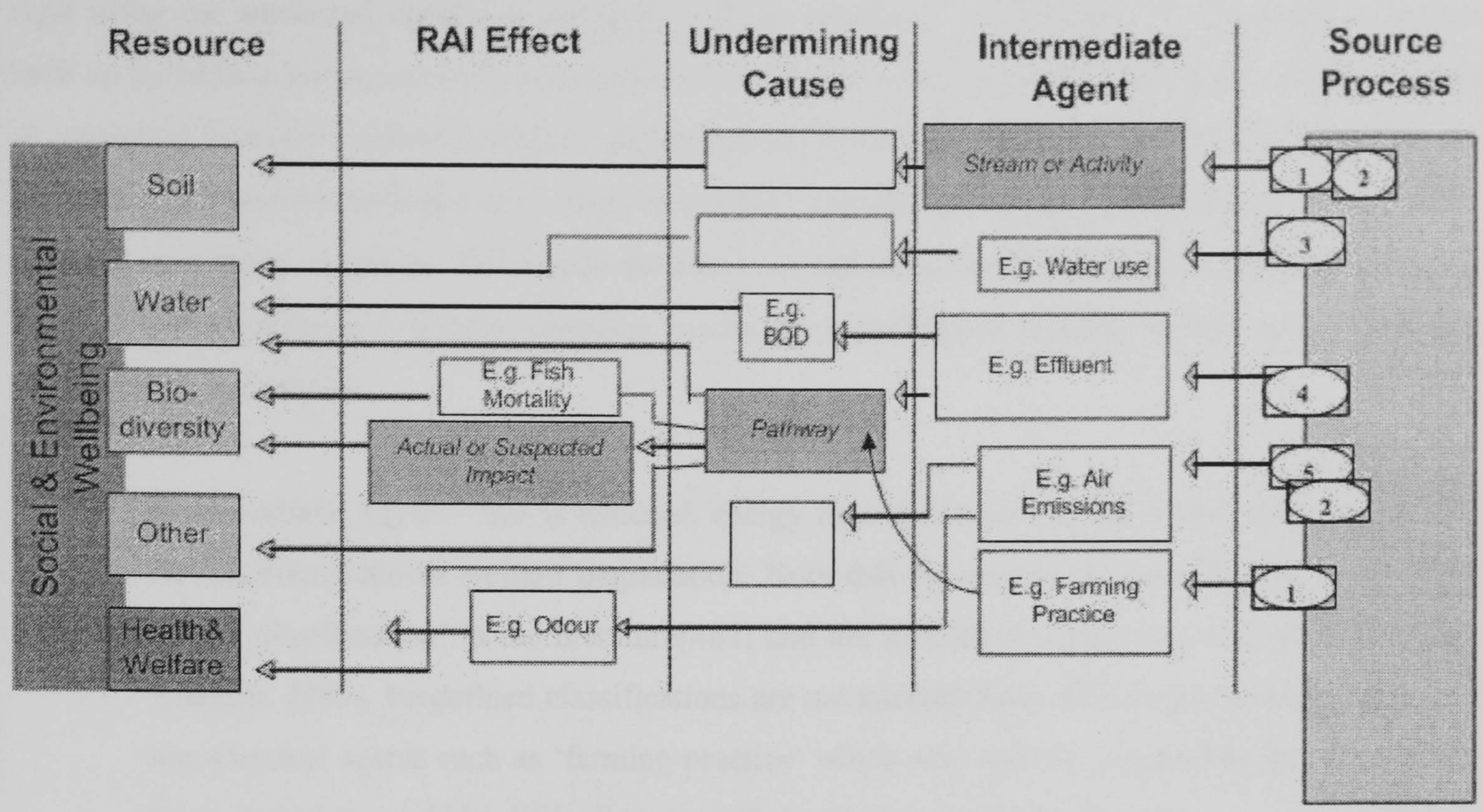
Figure 35 - Boundaries of Operational Control

8.2.2.3 Impact Assessment (c)

To satisfy requirement (c) above, there is a need for the impact assessment method to be consistent with the goal. In this thesis impact is defined in terms of natural and social resource availability infringement (RAI) – see page 35. A system is sustainable if it does not contribute to RAIs. The goal of sustainable systems places a different emphasis on the use of impact assessment: it is used in LCATS to provide information necessary to identify and appraise optional routes toward sustainable systems rather than to support an analytical decision. This means seeking processing options which maximise the availability of natural resources and aiming to deliver a system that could go on indefinitely. Progress towards the goal is achieved through the systematic removal of those processes or actions which cause resource availability infringement (RAI) in the first place.

There need be no debate over whether resource or toxicological impact should receive the greater attention: all environmental damage – whether consumptive or through pollution – ultimately removes the *availability* of resources. The term resource is taken here in its widest sense to include life support functions (see page 46) and other non-material requirements for need satisfaction and welfare. Within LCATS, a qualitative impact assessment method is operationalised through the use of a resource availability infringement link (RAIL) diagram (see Figure 36 and Figure 37). The purpose of this is to encapsulate information of known or potential RAIs resulting from the life cycle, by linking the source process(es) with potential resource availability infringements. The inventory items are supplemented with other features of processing which lead to infringement – such as intensive farming practice. The intention is to include both scientifically proven impact pathways and the more intangible or suspected links (i.e. putting the Precautionary Principle into practice). The RAI concept and RAIL diagrams are operationalised using a list of resources such as presented in Appendix A.

This impact assessment diagram provides crucial feedback on the environmental performance of a given life cycle by associating processing elements with their own set of impacts making the assessment process-orientated. In order to extract maximum value, impact assessment must now be coupled with feed-forward strategies before any significant progress toward a goal of sustainable systems can be made.



See Figure 37 overleaf for description and key.

Figure 36 - A Sample RAIL Diagram

The RAIL Diagram begins with the resources to be conserved on the left, and the source processes on the right using the numbered streams crossing the primary boundary – see Figure 35. The RAILs are then built up by linking known *stressors* with known or suspected *causal processes*; and finally with the *actual or suspected* resource availability effect (see definitions below). It is recommended that streams that are not part of the core processing route – such as ancillary supplies or common infrastructure and utilities – are kept in separate diagrams. The reason for this is to capture as much of the RAI characteristic to the main production route in a 'master' diagram, forcing the consideration whether the life cycle in question could *ever* be sustainable.

- **Intermediate Agent** – this is material, energy flow and/or action that is ultimately responsible for environmental or welfare degradation. Note that the process of collating this list is often called 'classification' in the literature[482] and the individual stream or action referred to as a 'stressor' [483]. Predefined classifications are not adopted here. This makes it easier to include non-physical agents such as 'farming-practice' which may well be responsible for causing RAI (even though it would be difficult to quantify in the classical LCIA manner).
- **Undermining Cause** – this is the casual pathway that links a given agent with an actual or suspected RAI effect (see below). This relates to 'midpoints' in the literature (see SETAC for example [484]) although here no quantification is made.
- **RAI Effect** – this is the known or suspected damage or other effect to a given resource. This is similar to the concept of 'endpoints' in SETAC/ISO terminology [485] but not identical: here the RAI effect is the *effect* to a given resource, rather than the *resource* that is damaged. Again quantification is not made here.
- **Resource** – these are the resources critical to life support and/or welfare. Note that damage is possible to welfare either directly or through loss of availability of other resources. Welfare is therefore filled in as the darker 'L' shape on the diagram to reflect this. Resources here approximate 'areas of protection' in the literature (see SETAC for example[486]). A list of typical resource types is discussed on page 46 onwards. Such a list cannot be exhaustive, and – since the purpose of LCATS isn't product comparison – the list can be widened or shortened to suit application. A predefined list also risks loss of flexibility and exclusion of resources that do not well fit such a list. In terms of impact to welfare in particular, future work is necessary to better understand how such RAI can be defined and/or captured. This is not well understood here or within the life cycle field in general. This does not however weaken its importance as an RAI to be addressed for a given lifecycle.

Figure 37 - Setting Up a RAIL Diagram

8.2.2.4 Improvement Assessment (d)

Improvement is commonly seen as an application of classical LCA, not a methodological step core to it (see page 103). To meet the needs of implication (d) above it is necessary to explicitly include an improvement assessment element within LCATS. This is a necessary stage in the whole procedure for attaining sustainable systems as depicted in Figure 34.

The objective of improvement assessment within LCATS will be to identify and appraise ways in which the RAILs – as set up within impact assessment – can be removed or continuously improved, thus moving toward the sustainable system goal of the assessment. Since it is unlikely that all resource availability infringements will be readily identified, the RAIL diagram cannot be completed and there may be impacts to resources that we cannot measure or are simply unaware of (see page 117). It is necessary therefore to carry out improvements both with respect to known or suspected RAIs and the more intangible impacts. The Precautionary Principle applied to this lack of perfect knowledge means that there is a need to exact best material and energy efficiency wherever possible *in addition* to the objective of removing individual RAILs.

Improvement options can be *identified* using feed-forward rule-of-thumb strategies (such as presented in Part I) and *modelled* using both the qualitative RAIL approach and quantitative data. Problem-orientated data can be used to provide *feedback* on the environmental performance of the life cycle (using the process control analogy on page 82 earlier). Quantitative data is of course particularly valuable in target setting.

8.2.2.5 Integration with Operational Management and Information Systems (e)

LCATS should be integrated with ongoing in-house operational management and information systems, and would be infinitely iterative. This is important since few can hope to deliver a sustainable company operation overnight. Furthermore, as discussed on page 145, existing products are likely to be mature – and the opportunity to affect the product at its inception has been lost. While it is argued that LCATS, or indeed any life cycle approach, would be best used an ongoing process, this may not always be desirable or appropriate. Under these circumstances, business would still be encouraged to continue the process at least until such times as improvements are implemented, allowing a follow-up exercise to see that the change delivers anticipated results.

A particularly useful way to implement LCATS into ongoing company operation would be through the use of an Environmental Management System (EMS). There is already evidence of a positive outcome of such combined effort [487].

8.2.3 Description of Life Cycle Assessment Towards Sustainability (LCATS)

Life Cycle Assessment towards Sustainability (LCATS) is an analytical and strategic business-focused approach for progressing towards the objective of sustainable systems, i.e. systems that could go on 'forever' without undermining social and environmental resources critical to welfare and life support (see definitions on pages 29 and 86). Based on life cycle assessment, LCATS aims to identify and evaluate opportunities to implement processes that maximise the availability of natural and social capital and avoid consumption and destruction of such resources. Accordingly, the tool employs a concept of 'resource availability infringement' at the core of impact assessment. This is coupled with a strategic improvement assessment which seeks out those activities that significantly and verifiably promote sustainability, helping business plan a course of action toward sustainable systems.

8.2.4 Framework

The framework for LCATS is:

1. Scoping (for an explicit goal of Sustainable Systems)
2. Inventory (based on mass and energy balance and other stressors)
3. Impact assessment (using Resource Availability Infringement Link (RAIL) profiling)
4. Improvement assessment (strategy based)
5. Decision making and implementation

See Figure 38 for a conceptual diagram of the LCATS methodology.

8.2.4 Goal Definition, Scope and Review

The individual steps are:

- Goal definition – this is predefined as the need to deliver ***sustainable systems***.
- Set scope (the terms of reference)
- Continually review the objective, scope and success of the study

The goal definition, terms of reference and review procedure is iterative. Initially, the point of the exercise is to set the terms of reference of the study. As the study progresses, the procedure will:

1. monitor the robustness of the study in terms of its boundaries (both in terms of system boundaries and other constraints such as project resources); and
2. review how well the LCA process is **achieving** the goal.

8.2.4.1 Goal Definition

The ultimate goal of this LCA based approach is the creation of **sustainable systems** (see definitions on pages 29 and 86). In short, the objective is to deliver a cradle-to-grave system providing the desired function in a way that does not infringe the availability of environmental and social resources (and could therefore go on forever). The practitioner may wish to set more specific targets in addition to this, but this ultimate goal of sustainable systems must be borne in mind at all points of the study, particularly with respect to review and improvement assessment. Where used, targets should be periodically reviewed for their robustness and appropriateness.

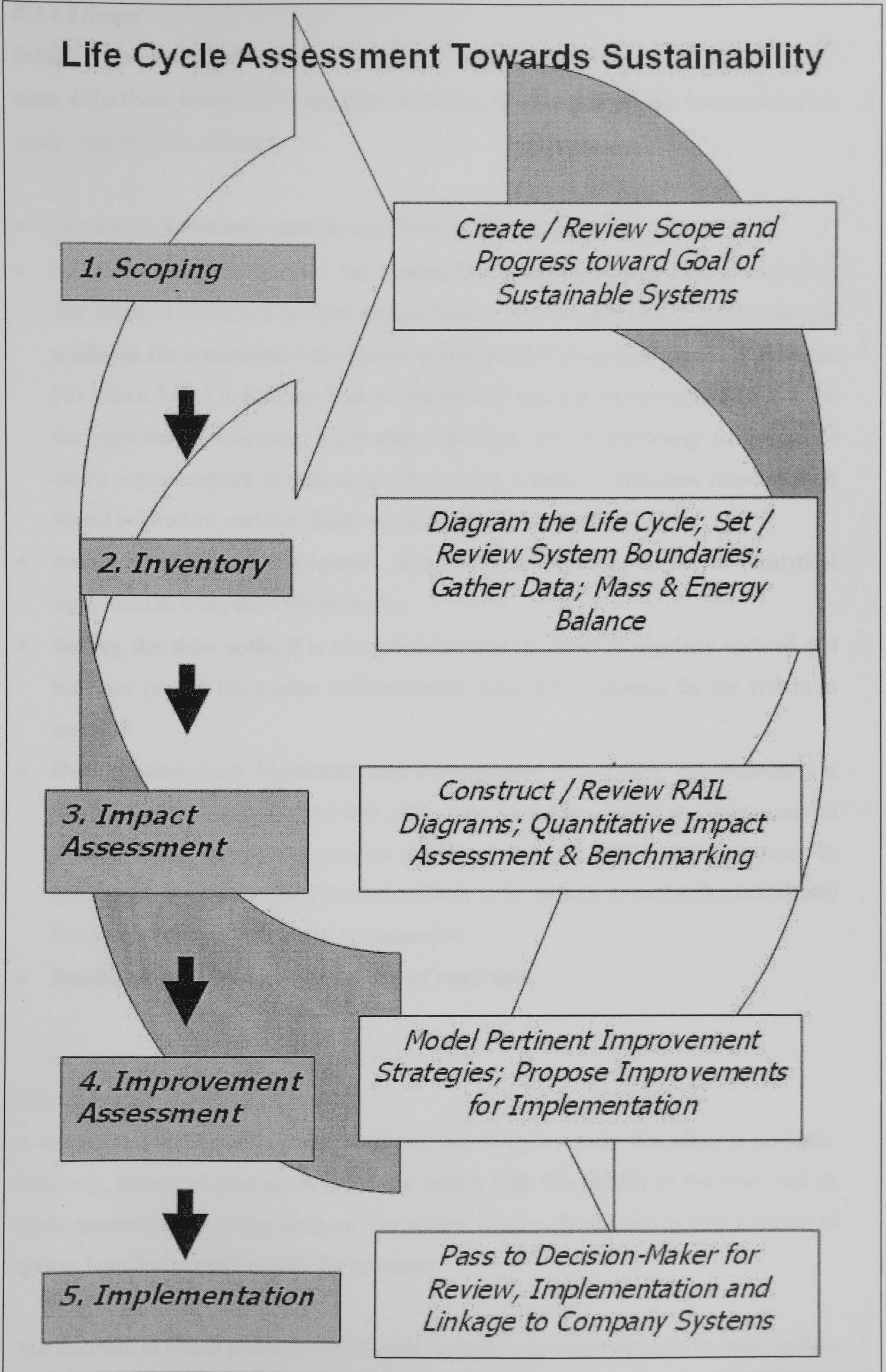


Figure 38 - Diagram of LCATS Methodology

8.2.4.2 Scope

Setting the terms of reference of the study – usually referred to as 'scoping' – is the aims, objectives, limits and constraints (including resources) that apply to the particular study. The exercise includes:

- **Setting the functional unit** (as described by ISO 14041) [488].
- **Initial boundary setting for the system.** Boundaries must ultimately extend from raw material extraction to final release back to the environment. It is important to subdivide the boundaries with relation to the level of operational control (see Figure 35). Since LCATS does not seek to describe an absolute environmental profile for the purposes of functional comparison, the strict ISO methodology for choice of which inputs/outputs to include is not required. Clearly a consistent rule-of-thumb would be prudent, and any decisions/assumptions documented.
- **Assigning resources.** Manpower, financial, and hardware resources (analytical equipment or computers for example).
- **Setting the time scale.** It is recommended that the study is regularly updated and becomes part of the routine environmental management process for the system in question.
- **Documenting study limitations and assumptions**. Data quality and availability is likely to be one limitation and ISO 14041 puts a number of prudent requirements on data quality [489]. Outwith process-specific data, the availability of appropriate or quality generic data is also a limitation likely to be directly related to funds available for the study - for datasets can be expensive.
- **Deciding upon methods and format of reporting.**

8.2.4.3 Review

A regular review of scope and constraints is necessary to ensure that effort is pertinent. Similarly, review of progress is critical to ensure both the validity of the study and its likely success in promoting the goal. The review process should also include a review of system boundaries employed in the inventory.

The decision at which point(s) to hold such reviews is an important one. In small studies – where the main effort will only focus on one LCA step at a time – it might be appropriate to hold the review at each full iteration of the LCATS process. In larger studies – where it is more likely that all stages will be worked upon simultaneously – it might be appropriate to hold these reviews at a regular interval, for example every 4 weeks.

8.2.5 Inventory

The steps involved in the inventory stage are:

- Diagram the life cycle
- Define boundaries – create or review
- Collect data
- Mass and energy balance

Many of these steps are complementary and will overlap.

8.2.5.1 Diagram the Life Cycle

Drawing up a life cycle diagram is arguably the most important exercise in the LCATS process. It is the life cycle diagram that generates the invaluable life cycle awareness to guide the study. It is likely that an informal version of this diagram already exists since some initial boundaries have already been drawn up during scoping. A formalised diagram will direct the data gathering exercise and can be used to clearly delineate where the boundaries of the analysis lie at any one point in time. It is important to use a systems approach in gathering/displaying the information on the diagram and directing the data gathering exercise. The material and energy streams can then be numbered and cross-referenced with the mass and energy balance.

It is likely that the life cycle diagram will continue to mature as the data gathering exercise is underway. It is important to uncover key features of the main processes involved as soon as is possible. This will significantly assist the boundary setting and data gathering exercises.

8.2.5.2 Define Boundaries

There are a number of different constraints on any LCA study. Boundary definition involves drawing up the boundaries that will dictate the data gathering exercise and the focus of the study from the inventory onwards. It is important to review these boundaries regularly and to extend them – as soon as resources will permit – back to raw material extraction upstream of the life cycle and final release back to the environment downstream of the life cycle, i.e. the primary flows. Note that without this cradle to grave scope it is impossible to fulfil the ultimate requirements of the goal of LCATS. Generic data will be particularly useful to sketch boundaries in at an early stage.

There are different types of boundary and methods that could be employed to set them. They could be drawn up geographically, in terms of ownership or responsibility, in terms of processing operations and so on. Generally, it is possible to demarcate between upstream, downstream and ancillary boundaries (Figure 29 on page 100). The decision where to cut off ancillary boundaries can be a difficult one, especially where lateral inputs or outputs from main process routes can link to other entire life cycles. Some practitioners use a process or rule-of-thumb by which to set boundaries. Given that no choice of boundaries is 'correct' [490] a fairly arbitrary setting of ancillary boundaries is acceptable here, provided that:

- the main process routes are fully represented;
- the location of the boundary is transparent (i.e. the life cycle diagram shows, with reasonable detail, what is outwith the boundary);
- the reasons for the decision to place a boundary are clearly communicated (this makes review of boundaries easier, and improves the clarity and integrity of the study);
- the chosen boundaries and the reasons for their selection are periodically reviewed;
- every effort is made to seek a sustainable system with respect to the boundaries that have been chosen.

The decision where to place upstream/downstream boundaries cannot be as arbitrary (see Figure 29 on page 100). The onus on the practitioner is to ensure that, ultimately, the whole life cycle of the main processing routes from raw material extraction to final release to the environment is covered. The recommended approach is to draw 'logical' boundaries around the differing levels of operational influence exacted by the company on its life cycle (see Figure 35). This brings benefits in helping make a manageable start to the study since its possible to start with a narrower portion of the life cycle and expand on successive iterations of the LCATS process. More crucially, such boundaries will help the company understand *where* current influence lies and where positive change can be made. Note that while it may be unfeasible (or impossible) to extend operational control to the whole life cycle, a general strategy for a sustainable system will be to extend the secondary boundary (i.e. operational *influence*) far enough to positively effect all areas of the system.

Figure 39 provides an example of the 3 operational boundaries (described in Figure 35) as applied to a hypothetical brewery.

8.2.5.3 Gather data

The data-gathering phase is probably the most resource intensive exercise of the LCATS process. Problems of obtaining information and doubts about its quality are not unique to the LCA field, but every effort should be made to ensure valid data is used. Life cycle specific data is to be preferred to generic industry average data, not least because this will improve the validity of the study and increase the likelihood of identifying improvement options. This is most likely to be available within the primary boundary identified in Figure 39. Data for the secondary and tertiary boundaries may have to come from generic sources.

Data is likely to be collected from a wide variety of sources and in non-consistent formats and measurement units. It is important to collate this information in a common format, using Système International (SI) units wherever possible (this is important for the purpose of constructing the mass and energy balance). Computer spreadsheets and databases are ideal for collating such information (the comma-separated value or CSV file format is particularly valuable because it is portable between common software packages). All data must be normalised using the functional unit of the study.

It is important to document sources of data, assumptions made, data age and confidence for review purposes.

8.2.5.4 Set Up Mass and Energy Balance

The use of process specific detail is important to the study as potential areas for improvement can otherwise be overlooked. An accurate picture of the mass and energy streams of the life cycle is best constructed using tried and tested techniques of the chemical engineering mass and energy balance. All inventory data is normalised using the functional unit. Energy quality (exergy) is an important indicator of the availability of energy to do work and should be included where possible (although commonly this may not be feasible). Consistent with the process-orientated approach taken it is useful to keep energy generation and combustion emissions in a separate part of the inventory so that the contribution of energy to the overall RAI profile of the life cycle is more readily apparent. Such practice is normal in chemical engineering. By also keeping transport data segregated according to the different operational boundaries it is readily apparent to what degree the company can influence RAI associated with transport during improvement.

To enable RAIL profiling, the points at which mass and energy streams cross the boundary of operational control (the 'primary' boundary) are labelled. Figure 39 shows the labelling of streams entering and leaving the primary boundary in the hypothetical brewing example [491]. Employing chemical engineering practice here means allocating a unique identifying number to these streams, such that the data can be readily corroborated with the diagram. This practice will assist in the later impact and improvement stages of the LCATS procedure.

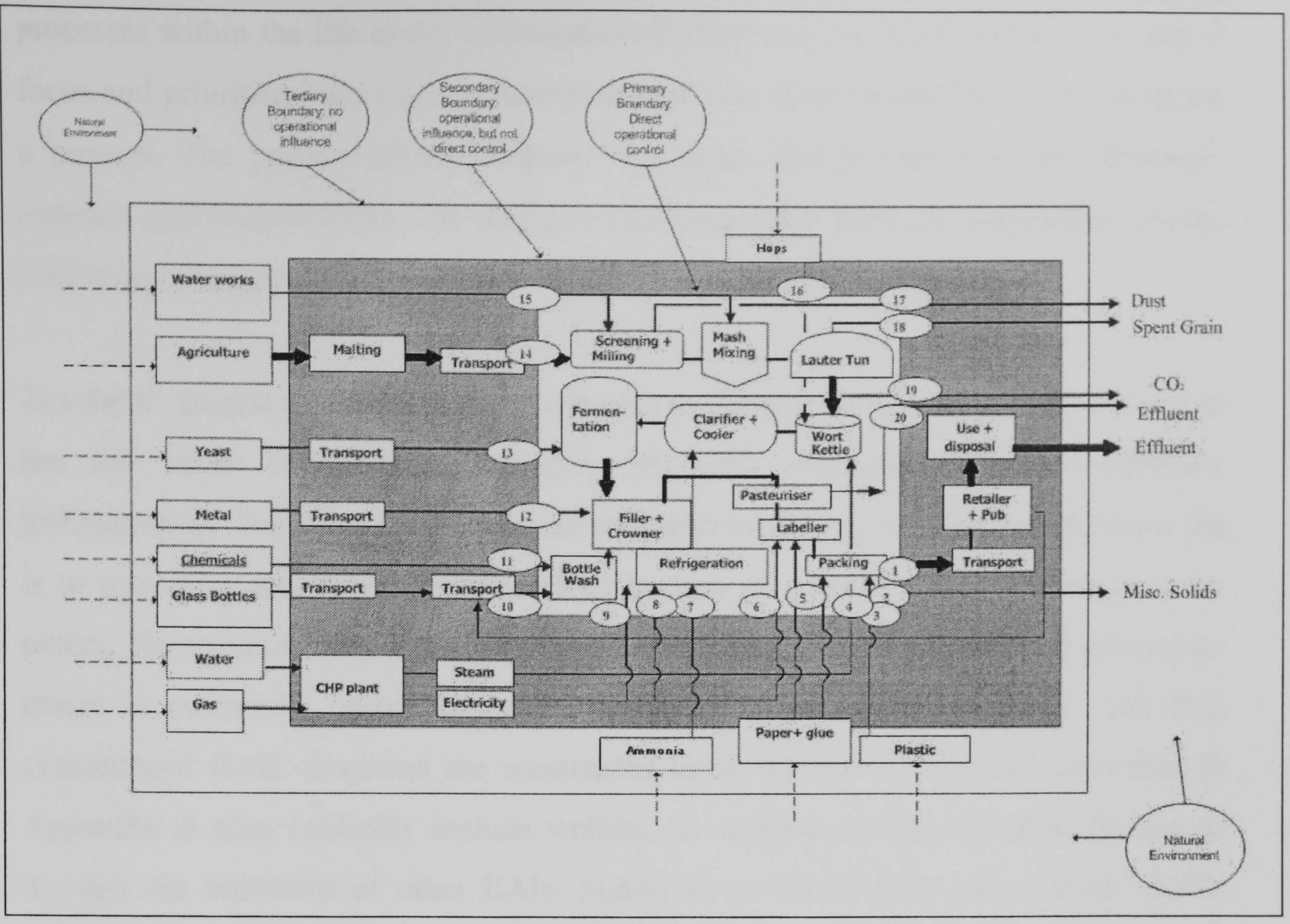


Figure 39 - Beer Production: a Hypothetical Brewery

8.2.6 Impact Assessment

Impact assessment in LCATS is predominantly a qualitative, conceptual approach linking the streams from the source processes identified in inventory to known or suspected resource availability infringements (RAIs).

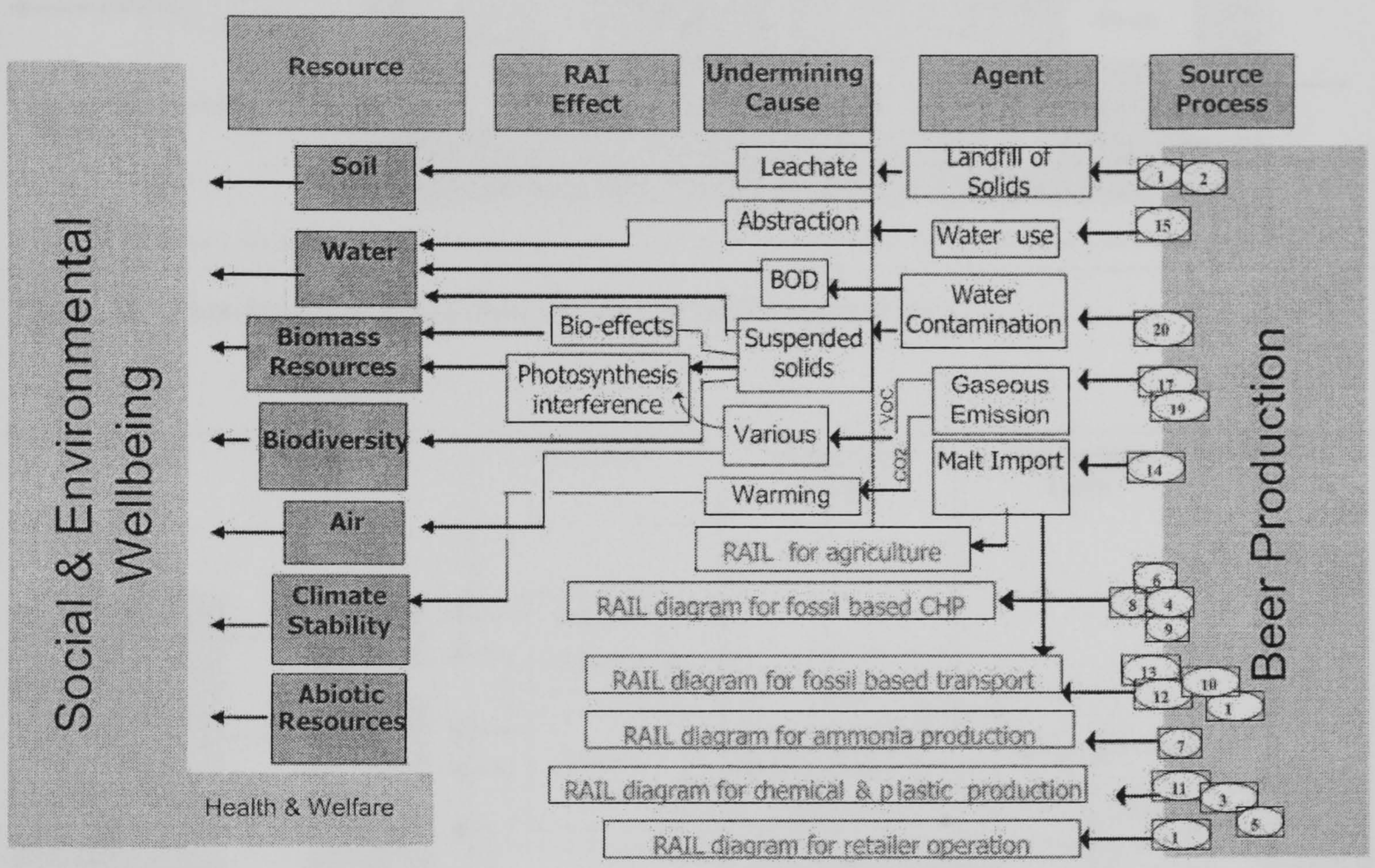
8.2.6.1 Construct the RAIL Diagram

There are numerous published impact assessment methodologies; most are quantitative in nature to support the use of LCA as an analytical decision-support tool. Impact assessment within LCATS has a different emphasis from that required by the classical LCA. Here it is used to understand what needs to change in order to achieve the *goal* of sustainable systems, or to assess progress, towards that goal. There is increasing interest in 'top-down' approaches to impact assessment in the literature which – as is the case here – begin with the resources to be protected, i.e. begins with the valued item [492]. Rather than present environmental impact as a series of discrete impacts or graphs depicting problem-orientated, aggregate impact data, the objective of impact assessment in LCATS is to provide a profile that describes the unsustainable elements of particular processes within the life cycle. Examination of RAIs and the RAIL profile will help to focus and prioritise improvement assessment options which invariably means changing a process. The purpose of the diagram is to help *identify,* and therefore ultimately *mitigate,* and *remove* RAIs. The diagrams also ensure that there are placeholders for the full range of impact whether known, or suspected; measurable or intangible.

The RAIL diagram (Figure 40) is constructed by linking the source process streams in the life cycle flow diagram (Figure 39) with potential resource availability infringements. The diagram is to include both scientifically proven impact pathways and is to provide placeholders for intangible stressors or suspected links (as required for putting the Precautionary Principle into practice). The identification of stressor-impact chains is essentially 'classification' in the ISO/SETAC LCIA framework. The RAI concept and RAIL diagrams are constructed using the list of resources presented in Appendix A also explicitly include welfare, as welfare can be impacted directly or through the existence of other RAIs. Figure 40 overleaf shows the 'master' RAIL diagram for the hypothetical brewing example which includes RAIs under the direct responsibility of the company together with placeholders for those other RAIL diagrams arising elsewhere in the life cycle.

In the diagram, that RAIs associated with streams entering and leaving the operational boundary are at the top of the RAIL diagram. In terms of practicality, it will make sense to tackle these RAIs first as the company will have direct control over 'primary' streams, which are those inputs and outputs passing directly to/from the environment by crossing this boundary, such as air emissions for example. Extending this guideline, it makes sense to group RAILs for the secondary boundary processes next, and tertiary boundary processes at the bottom of the diagram. The RAIL profiles for auxiliary support processes and services should be created and kept separately. For the hypothetical brewery, these will include RAILs for power generation, transport, agriculture and so on. Figure 41 is an example flow diagram and Figure 42 is the corresponding RAIL diagram, for gas-based CHP. This is not under direct control of the company, but is under its 'influence'. As such, the RAILs have not been *numbered*, but *alternatively labelled* and ultimately attributed to the associated process in the master RAIL diagram. Thus all CHP RAIs are inherited by streams A & B - electricity and steam - and then associated with corresponding streams 4, 6, 8 and 9 on the beer RAIL diagram as demanded by usage.

Work to further develop the RAI concept has already begun at Heriot Watt University [493] and the incorporation of less readily quantifiable stressors such as noise or effects of farming practices is being reviewed. There is also a need here to develop a means of assessing impact on welfare within this sustainability framework.



Note that flow and RAIL diagrams for fossil based CHP may be found in Figure 41 and Figure 42 respectively. RAIL diagrams for ammonia production, the retailer operation and so on would need to be drawn up to describe the life cycle fully.

Figure 40 - RAIL Diagram for Beer Production

A further example of a flow diagram for a hypothetical papermill – with associated RAIL diagram – is provided on page 184, i.e. Figure 43 and Figure 44 respectively.

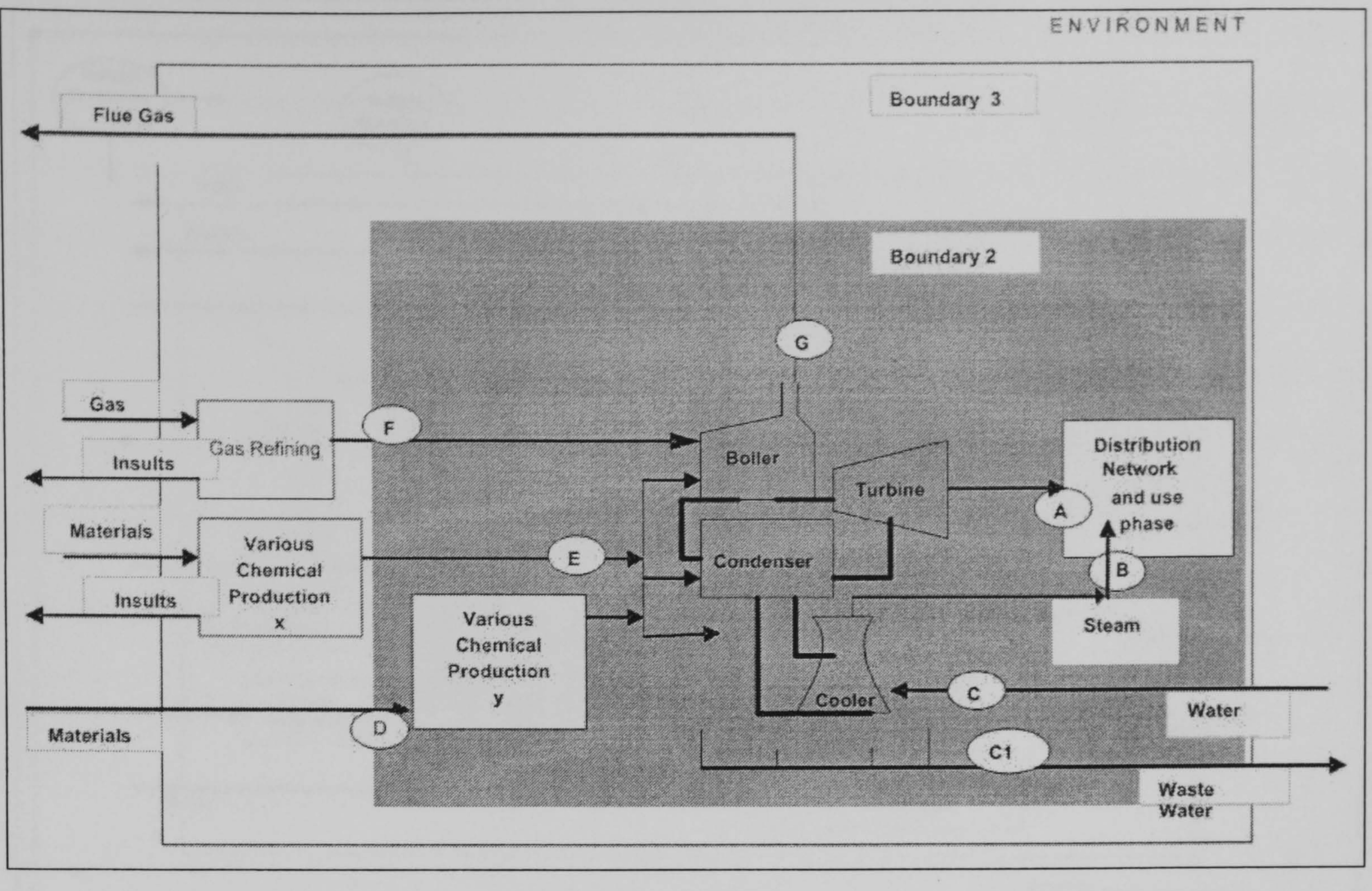


Figure 41 - Flow Diagram for Ancillary CHP (for Beer Production)

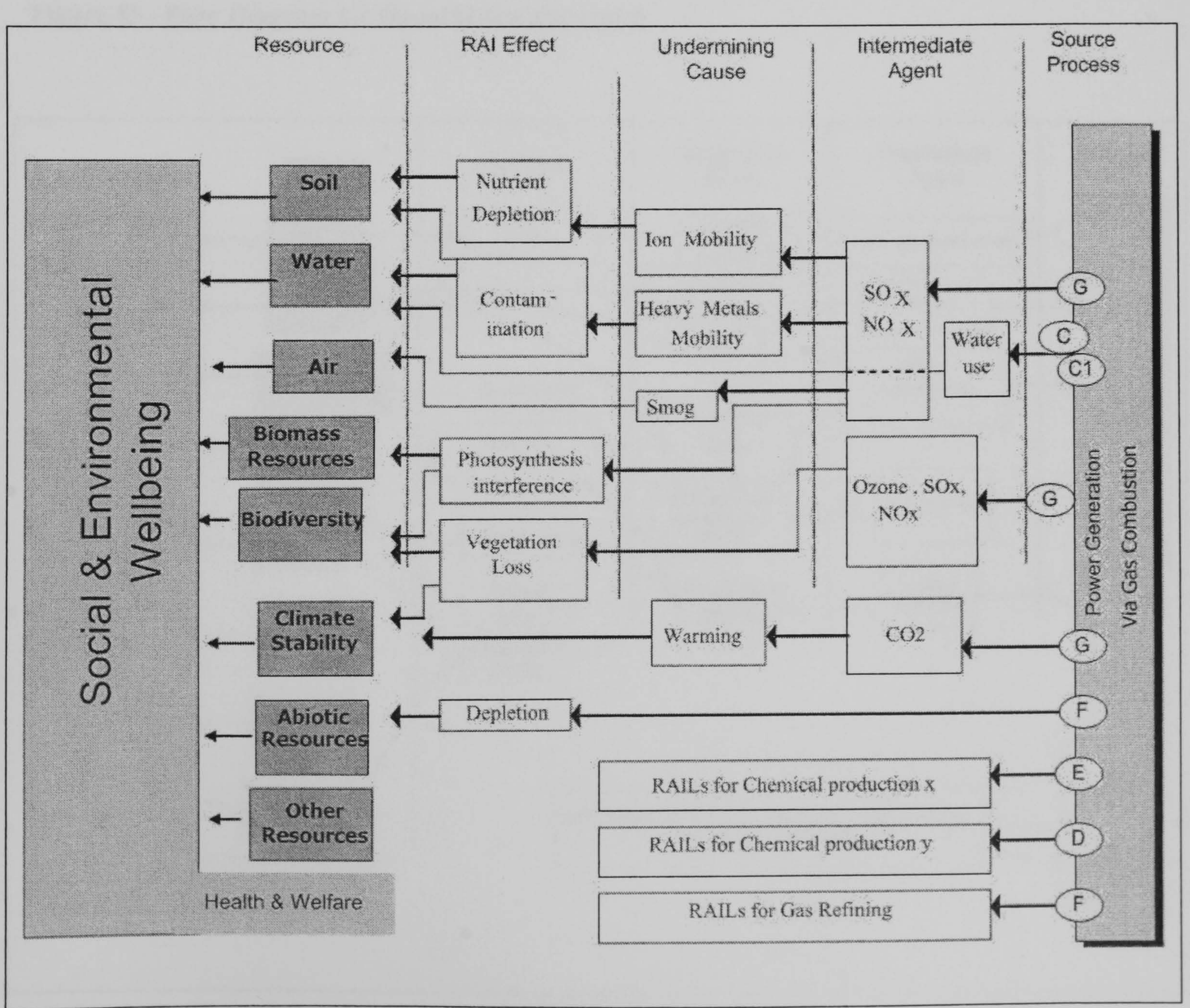


Figure 42 - RAIL Diagram for Ancillary CHP (for Beer Production)

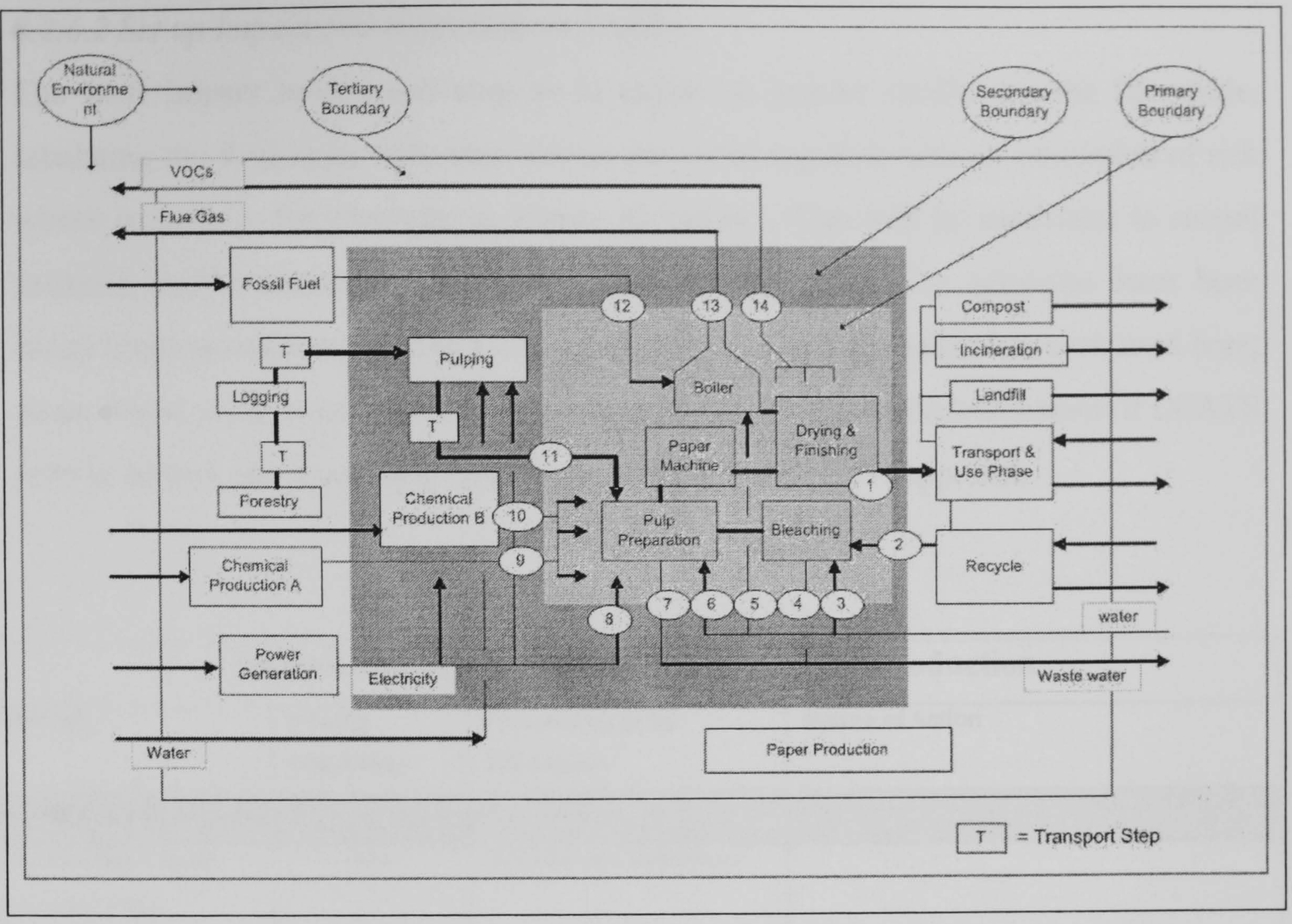


Figure 43 - Flow Diagram for Hypothetical Papermill

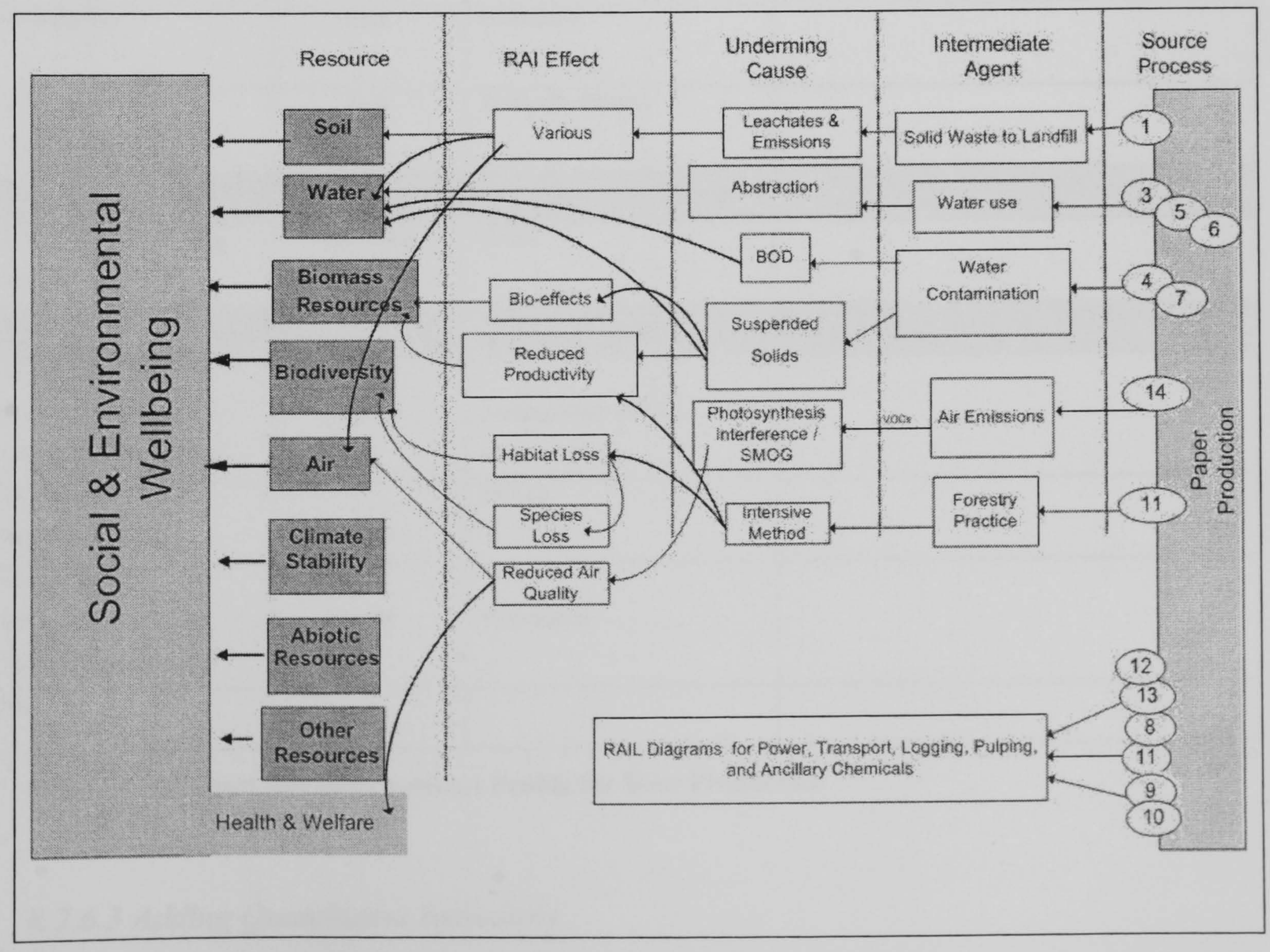


Figure 44 - RAIL Diagram for Hypothetical Papermill

8.2.6.2 Set up Impact and Improvement Profile

The next impact assessment step is to create an impact profile for the life cycle, tabulating the RAI links with their source processes together with an estimation of risk where possible – see example in Figure 45 below . This will be used later to record possible improvement options for the processes involved. The priorities have been based upon an assessment of risk of a given effect. Prior knowledge has been used here; some future work is necessary on rule-of-thumb priorities or risk/assessment if LCATS is to be turned into a one-stop cookbook for a qualitative LCA approach.

Impact and Improvement Profile for Beer Production			
RAI Link	**Priority Effect/Risk**	**Processing to be Influenced**	**Nature of Action**
Primary Boundary Effects			
2,18. **Landfill – spent grain; site waste.** Soil; air; water.	Low	Site waste inc. spent grain.	
19 **Carbon Dioxide** Air; Climate.	Low	Fermentation.	
20. **Effluent**	Med	Pasteuriser.	
17. **Dust** Air; Biomass	Low	Milling/Screening	
Secondary Boundary Effects			
1. **Landfill - packaging** Soil; air; water.	Low/Med	Retail.	
Tertiary Boundary Effects			
14 – **Malt Import** Biomass; Biodiversity; Water; abiotic resource	HIGH	Milling/Mash Mixing	
15 – **Water** Water abstraction.	LOW	Milling	
16 – **Hops** Biomass; Biodiversity; Water; abiotic resource	LOW	Wort Kettle	
etc.			

Figure 45 - Impact and Improvement Profile for Beer Production

8.2.6.3 Adding Quantitative Indicators

Finally, as an optional step in order to help monitor progress toward sustainable systems, it is possible to ascribe some quantitative indicators. These could be used to set operational efficiency targets and to evaluate improvement options. This data is particularly helpful in dealing with a mitigated RAIL, i.e. one where the stress might be reduced, but not eliminated – as part of a 'transitional' response (see page 63). Such indicators may include percentage renewable electricity contribution, flue gas flow rate and composition etc.

8.2.7 Strategic Improvement Assessment

The purpose of the strategic improvement assessment stage is to maximise the availability of natural resources by identifying and appraising improvement options for the life cycle in question. The ultimate goal is to remove all resource availability infringement links as identified in the RAIL diagram and thereby deliver a sustainable system. This is unlikely to be possible without extending a degree of operational influence over the *whole* life cycle, in order to affect positive change. The link removal procedure itself serves as a useful general business strategy and this is why the distinction between primary, secondary and tertiary boundaries is particularly useful - it dictates what can readily be targeted for improvement.

The steps involved in strategic improvement assessment are:

1. Generate potential improvement options for eliminating RAIs in the first place, or mitigating RAIs as a tactical interim response which can be bettered in the future.
2. Review improvement options, including modelling where necessary.
3. Update impact and improvement profile with the possible options in place.

8.2.7.1 Generate Potential Improvement Options

The ultimate objective of improvement assessment – and indeed of LCATS itself – is to eliminate all resource availability infringement links (RAILs), and thereby deliver a sustainable system. Elimination of all life cycle RAILs will not be possible 'overnight', and there will be a transition period during which such factors as national energy and transport infrastructures must change (see page 63). Accordingly improvement assessment will also seek means to mitigate RAILs which cannot yet be eliminated whether for technical, political, economic or other reasons. The point of the assessment is to generate a wide range of improvement options in the absence of economic constraint in particular. When favourable conditions arise, options for improvement will already have been identified and can be implemented accordingly.

Two complementary approaches are taken towards improvement assessment namely through RAIL elimination and through mitigation (a 'transitional' action). The point of the exercise at this stage is to generate *potential* improvement options, which are reviewed in a subsequent step. In order to avoid overlooking any improvement opportunities, strategies for sustainability (discussed in Part I on page 49 onwards and summarised in Figure 46) are used. Employing a process-orientated approach, the formal improvement generation procedure is as follows:

- Beginning with the primary boundary, apply all the improvement strategies one-by-one to see if there are opportunities to either eliminate or at least mitigate RAILs on the RAIL diagram. While carrying out this procedure, particular attention should be paid to any inputs or outputs *direct* to the environment from this boundary since *full operational control* may be exacted over these streams.
- Moving into the secondary boundary, the process of examining all the strategies for improvement is repeated, *including* the processes within the primary boundary in case this more holistic view reveals a different perspective. Again, any inputs or outputs *direct* to the environment from this boundary deserve special attention. Additionally, some processes could be brought under operational control by moving them from the tertiary into the secondary boundary. This will allow them to be redesigned for sustainability.
- Move onto the tertiary boundary, and repeat the process of examining all the strategies for improvement, and *include* primary and secondary boundary processes (in case this full life cycle or *system* view reveals a different perspective). The bulk of the *direct* inputs and outputs to/from the environment are here. so pay attention to any processes that may attract positive affect on the RAIL diagram by moving under direct operational control or influence of the company.

Having recorded the various *unconstrained* improvement options, these now pass to the review stage.

Summary of Improvement Strategies

Minimising Consumption and Destruction of Natural Capital (Conservation)

- *Efficiency in Material and Energy Use:*
  - Seeking material and energy efficiency.
  - Seeking to provide service rather than products.
  - Appropriate application.
  - Quality not quantity.
  - Use locally.

- *Minimising Damage:*
  - Product stewardship.
  - Seek zero emissions.
  - Apply risk assessment and the principle of precautionary action.

Maximising the Availability of Materials within the Socio-economic System (Enhancement)

- *Industrial Ecology.*

- *Maximise the utility of materials in the socio-economic system*
  - Implement sustainable power generation.
  - Reuse.
  - Remanufacturing/Reconditioning.
  - Recycling.

Note that these strategies are described in their full in Part I, from page 49 onwards.

Figure 46 - Summary of Improvement Strategies

8.2.7.2 Review and Model Improvement Options

The purpose of this stage is to review the unconstrained list of potential improvement options and decide which to recommend for decision-making and implementation, with a degree of prioritisation where possible. At this stage, some options might be dropped altogether – others might be 'parked' pending further information or assessment.

The various *unconstrained* improvement options are now entered on the impact and improvement profile as shown in Figure 47. Clear improvements can be recommended for immediate implementation while improvements requiring changes to a level of operational support will need a decision-making exercise. Marginal improvements may need further data and/or sensitivity analysis performed. The use of sensitivity analysis can be complex however, so it may be preferable to find more clear-cut improvement options. All potential improvements should however be recorded until such time as they are either implemented or ruled out.

To help the review process, it is useful to consider whether a given option:

- Can eliminate or mitigate a RAIL.
- Makes sense as it stands, or requires further information or modelling.
- Requires a change of boundary or not.

An improvement option that can eliminate a RAIL and which does not require modelling or change of boundary is clearly a 'quick win'. An option that might mitigate a RAIL, requires a change of boundary and has some uncertainty requires modelling is going to prove more of a challenge. Of course the various options are not always going to be so clear-cut. An improvement option may exist to eliminate a RAIL link – and is therefore a preferred option – but cannot be implemented because currently there is no means to bring about its implementation. At least the option is on record should conditions change favourably in the future to allow its implementation. In the interim however, the company may choose either to: (1) to seek ways to influence this area of the life cycle or (2) seek to mitigate the RAIL using other options which it is able to influence.

Care needs to be taken where improvement options *mitigate* rather than *eliminate* RAILs. Pure efficiency improvement may be obvious and will not need further review or modelling before implementation. Other options must however be screened throughout the rest of the life cycle in order to minimise the risk of problem-shifting, where an improvement in one place has an adverse effect elsewhere. This is particularly pertinent during the 'transition' period toward sustainability. Such screening is achieved by examining the differences in the life cycle model before and after the potential improvement, performed using either inventory data or the RAIL approach - or both.

Updated Impact and Improvement Profile for Beer Production			
RAI Link	**Priority Effect/Risk**	**Processing to be Influenced**	**Nature of Action**
Primary Boundary Effects			
2,18. **Landfill – spent grain; site waste.** Soil; air; water.	Low	Site waste inc. spent grain.	Seek composting for grain; better segregate
19 **Carbon Dioxide** Air; Climate.	Low	Fermentation.	Possible to recover CO2, compress and supply for use in soft drinks.
20. **Effluent**	Med	Pasteuriser.	Reduce BOD on-site.
17. **Dust** Air; Biomass	Low	Milling/Screening	Better air filtration.
Secondary Boundary Effects			
1. **Landfill – packaging** Soil; air; water.	Low/Med	Retail	Recover packaging.
Tertiary Boundary Effects			
14 – **Malt Import** Biomass; Biodiversity; Water; abiotic resource	HIGH	Milling/Mash Mixing	Acquire organically grown material and preferably from a supplier encouraging use of crop rotation, hedgerows etc.
15 – **Water** Water abstraction.	LOW	Milling	Use treated rainwater and/or recycle site water.
16 – **Hops** Biomass; Biodiversity; Water; abiotic resource	LOW	Wort Kettle	Acquire organically grown material and preferably from a supplier encouraging use of crop rotation, hedgerows etc.
Etc			

Figure 47 - Updated Impact and Improvement Profile for Beer Production

8.2.8 Decision-making & Implementation

With the improvement work complete, for the first iteration, it is up to the LCATS practitioner to present recommended improvement options back to the decision-makers. It is at this point that economic filters must necessarily be re-applied, after their removal during the earlier phases.

Low cost quick-wins are always more likely to be preferable to business than options requiring greater investment – particularly if there is no clear payback. It may be that legislation or prevailing economic constraints make such improvements financially unfeasible, but at least such options are open should the situation change. In the meantime, ways must be sought to implement improvement where economics supports or rewards the outcome. Where this is not the case, the economics should be kept away from the assessment. The business will also not want to overlook the potential promotional value of improvements made on the basis of LCATS. Stronger comparative environmental claims of product superiority – which have proven controversial in the past – or external comparison with competitor products should not be made without a more rigorous adoption of the standards set by ISO.

8.3 Discussion & Conclusions

LCATS has been presented as a complementary approach to its more analytical and complex LCA counterpart. LCATS is 'an approach' rather than a methodology *per se* since it includes a predefined goal and is proactive in the sense that it formally includes strategies for improvement option generation toward this objective. The practitioner using LCATS must be able to acknowledge the goal by seriously questioning whether a given life cycle can ever approach sustainability. If this is unlikely, then the recommended course of action would be to close the 'sustainability gap' defined below (see Figure 48) as far as is possible, while options for diversification into more sustainable business for the longer term are considered.

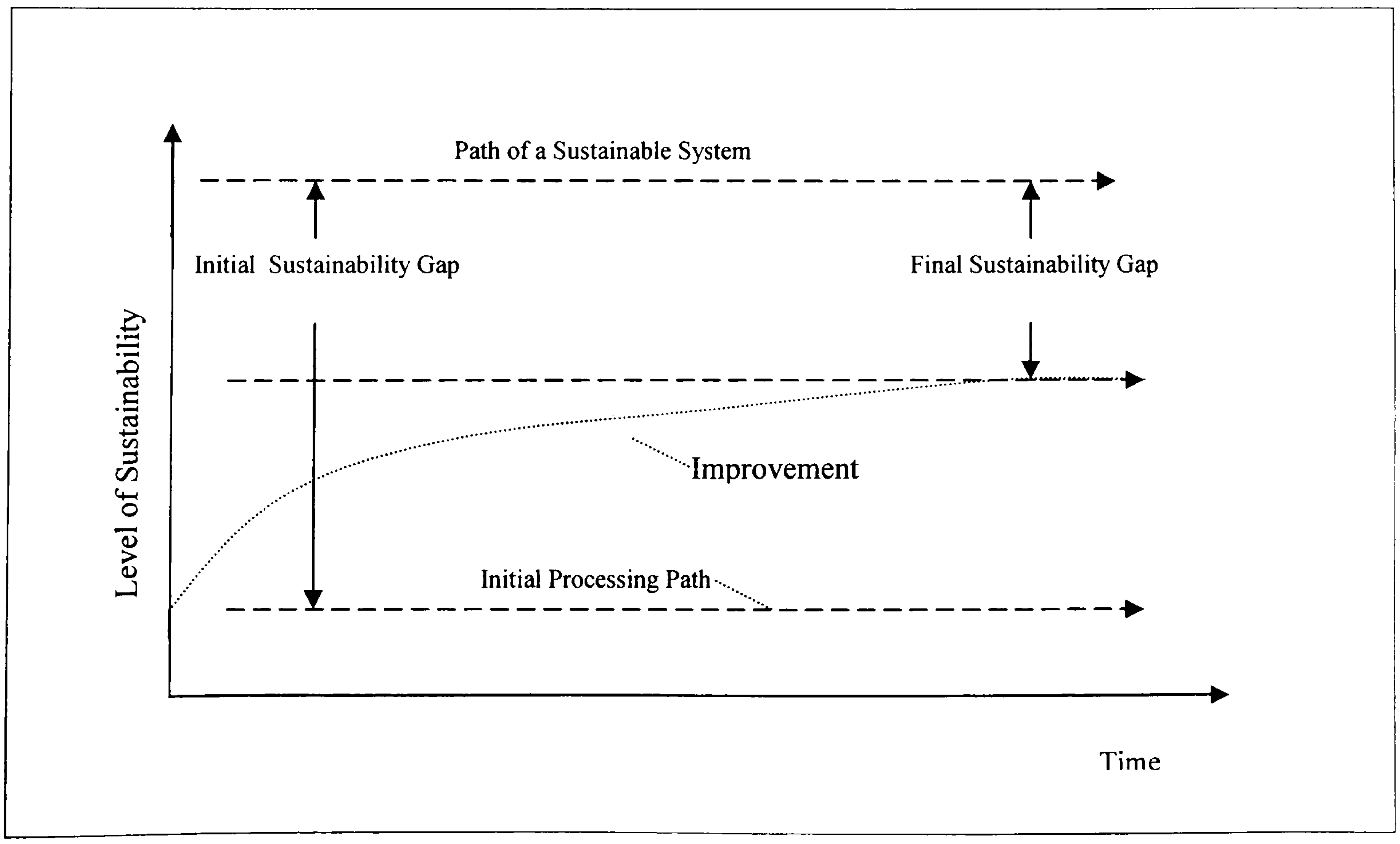


Figure 48 - Sustainability Gap

The 'sustainability gap' - described in terms of resource availability infringement - is the unsustainable features of a life cycle or system that define either (a) the challenges to be overcome in reaching a sustainable system and/or (b) reasons why the system will *never* be sustainable in the longer term. Taking the brewery example as it stands, the associated RAIL diagram (Figure 40) reveals that much of the challenge for the brewery in delivering a sustainable system for beer lies with infrastructure and suppliers, i.e. these are operations that are currently outwith direct operational control of the company. Transport and energy form a large proportion of such unsustainable processes outwith direct company control the company, yet remain *implicit* to the operation and its long term viability [494] (see Figure 49). This is likely to be the case for a great majority of other companies big or small.

Already LCA encourages users to 'think outside the square' in the sense that a holistic approach is taken to environmental issues. For example it is possible to view the energy use of a given process within a wider context and examine the percentage of total *life cycle* energy use attributed to the process itself. With LCATS, it is hoped that practitioners will 'think outside the box', taking a further dimension by recognising that influence over the long term sustainability of a company's operation need not lie merely with those operations currently under its direct control. Infrastructure is core to the long term sustainability of systems as some academics have observed (see page 129), but this does not diminish responsibility where influence can and should be extended. The LCATS process of working through improvement strategies within the differing boundaries of influence encourages awareness of what can and might be changed, or influenced, for the better. In the brewing example, the company could:

- Positively affect agriculture by either seeking ownership, or choosing organic suppliers.
- Use biomass-fuelled CHP on site and/or seek renewable energy supplier (or both).
- Use ownership, partnership or tender conditions to positively affect transport (e.g. LPG or bio-diesel blend).
- Send spent grain for composting.
- Collect and filter rain water on-site.

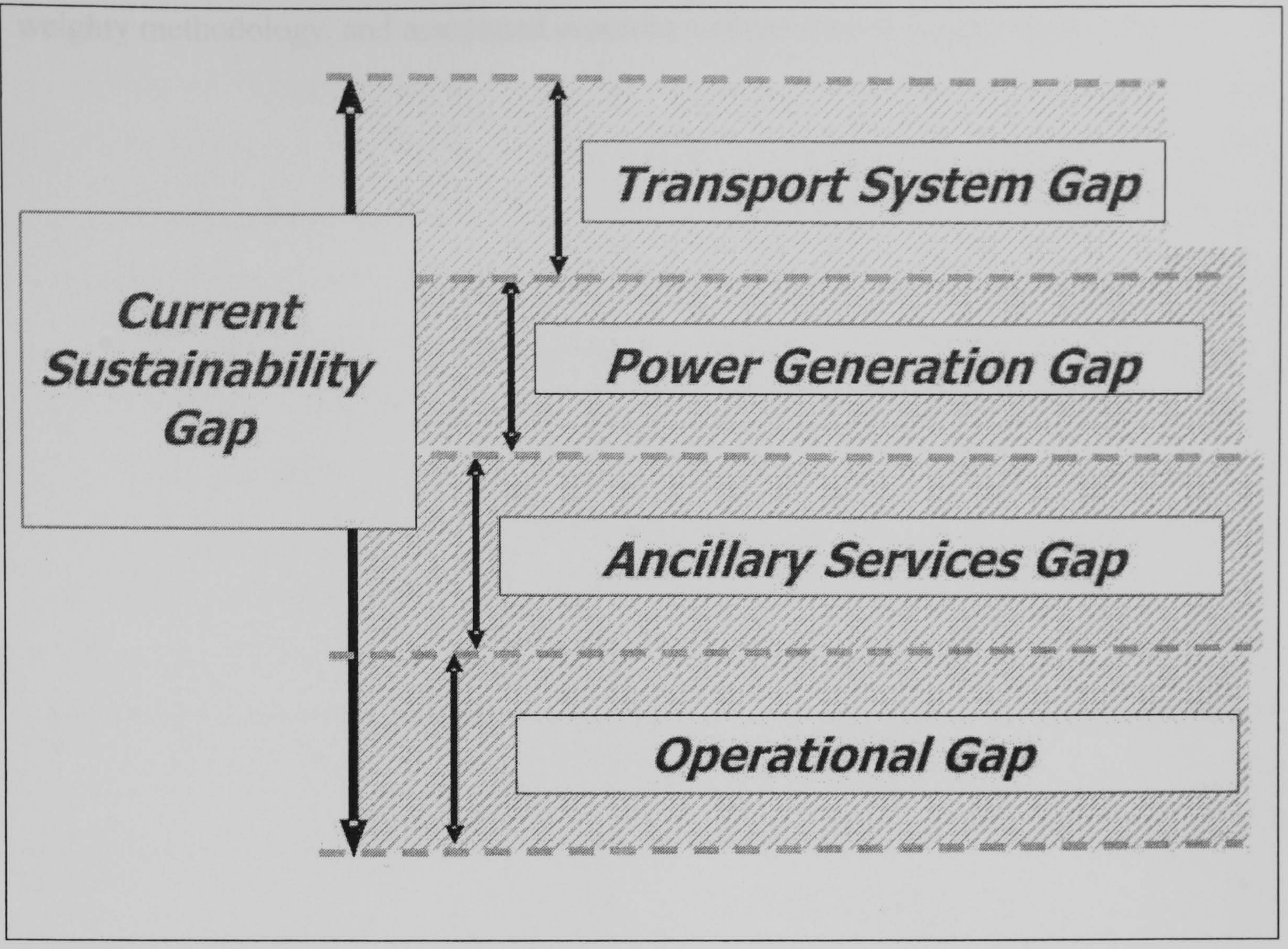


Figure 49 - Sustainability Gap: A Closer Examination

Fundamental to LCATS is the desire to assist users – particularly business – to know *what* to do in general in order to become more sustainable and also to do this within the life-cycle framework which provides the necessary systems perspective, and discipline minimising potential for problem-shifting. Strategies for improvement are deliberately generic – so that they might be relevant to the widest possible scope of application – yet sufficiently comprehensive to stimulate a broad range of potential solutions. Emphasis on drawing up a plan of action for moving toward sustainable processes rather than seeking to rank or otherwise trade-off disparate impact data encourages the user of LCATS to consider whether a given process, material, element or the whole system has the potential to be – or can be made to be – sustainable. By employing both feed-forward and feed-back elements, LCATS would probably be most beneficial when used as a process within the ongoing operational management of the company – providing both strategy and corrective feedback. This is done – as far as is possible – without economic influence since it is important to identify the *preferred* options should economics prove favourable. Finally, by avoiding unnecessary complexity wherever it adds little value, the approach should attract a new audience for LCA. This will include small businesses who seem to have been put off by the depth and detail of LCA, its weighty methodology, and associated costs for software and/or consultancy.

Chapter 9 – Appraisal of LCATS

9. Objectives

The main research question asked:

> **How should LCA methodology be configured such that it better promotes environmentally sound product systems, and thereby sustainability?**

This chapter concludes the answer to the research question by appraisal of the LCATS methodology presented in chapter 8. LCATS is applied to a published study on Linoleum, and differences in the approach taken and nature of the results are examined.

9.1 Introduction

Chapter 8 presented an LCA approach with a predefined goal of sustainable systems. This chapter seeks to appraise the LCATS approach by applying it to a published study: *Environmental Life Cycle Assessment of Linoleum* by Gorrée, Guinée, Huppes and van Oers at CML [495]. The work was commissioned by Forbo-Krommenie B. V.

Linoleum is a particularly interesting product in the context of this thesis – made largely from renewable raw materials, the product has the potential to be delivered as part of a sustainable system. However the decision to select the publication by Gorrée *et al* as the basis of this appraisal was made because the study was recent; and represented use of a classical detailed LCA largely compliant with ISO standards. Although Forbo-Krommenie B. V. is the world's largest producer of Linoleum [496] – production of a flooring product is a possible SME concern.

The following section is an iteration of the LCATS process as applied to the study published by Gorrée *et al.*

9.2 Application of LCATS to Linoleum

9.2.1 Goal Definition and Scoping

Goal definition for LCATS is predefined as the delivery of a sustainable system, therefore in this specific case, the goal is *to deliver a sustainable system for Linoleum.* The level of sophistication will be less than a classic detailed LCA, and the information and results would be intended for internal use only.

The **functional unit** selected by Gorrée *et al* is maintained here as *the use of 2000m^2 Linoleum in an office or public building over a period of 20 years.*

The **primary boundary** for the LCATS study encompasses the linoleum manufacturing site (direct operational control). The **secondary boundary** (operational influence) encompasses both manufacturing and processing under some degree of influence by the company – this is essentially the same as direct control since it has been assumed that all services and transport are contracted out to third parties (see list of assumptions below). The **tertiary boundary** encompasses all operations, including those outwith any influence of the company, e.g. raw material extraction.

A number of assumptions have been made to enable this study using the information published by Gorrée *et al*:

1. VOC emissions are principally from the calendaring and drying stages.
2. Mixed solid waste stream from the site goes to landfill.
3. Transport and product distribution is assumed to be contracted out on the basis of least cost.
4. Electricity and other utilities assumed to be bought on the basis of least cost.
5. Intensive monoculture practice in agriculture and forestry is assumed.
6. There is no form of lease model currently in place.

9.2.2 Inventory

The first step of the LCATS inventory process is to **diagram the life cycle**. Figure 50 – adapted from Gorrée *et al* – represents the cradle-to-grave life cycle of the Linoleum system. In Figure 51 the boundaries showing varying degrees of operational control or influence over the life cycle are delineated. These have been assumed for the purposes of this LCATS study, and follow the scheme set out in the previous section. These boundaries represent the **initial boundary setting** exercise and would be reviewed on subsequent iterations of the analysis.

Next in the LCATS process **data is gathered** and set up the **mass and energy balance** is set up. The data published by Gorrée *et al* is limited, but is sufficient to construct a basic mass balance here as shown in Figure 52. In this mass balance the unit operations are labelled P1, P2 etc as given in Figure 50.

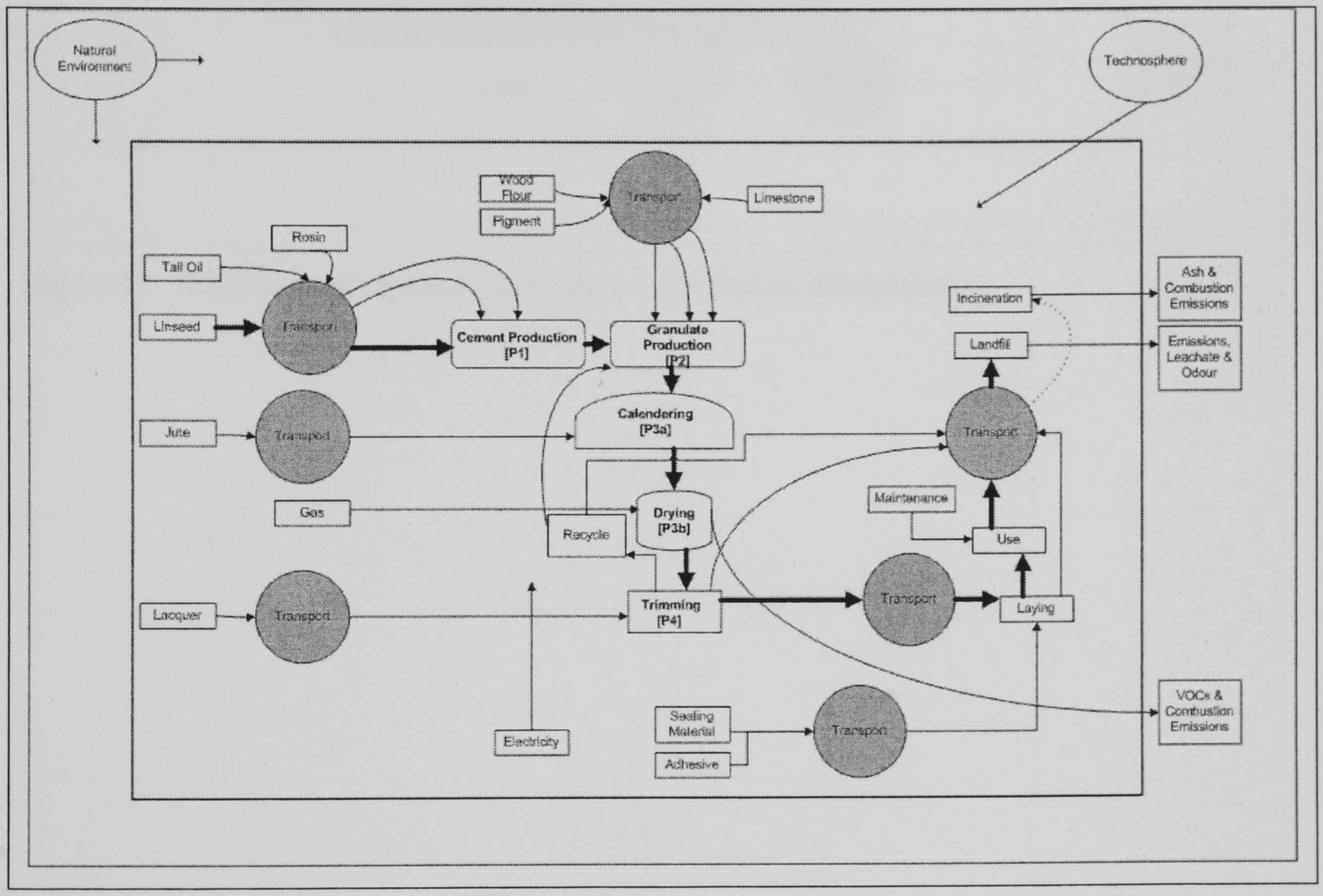


Figure 50 - Life Cycle Flow Diagram for Linoleum

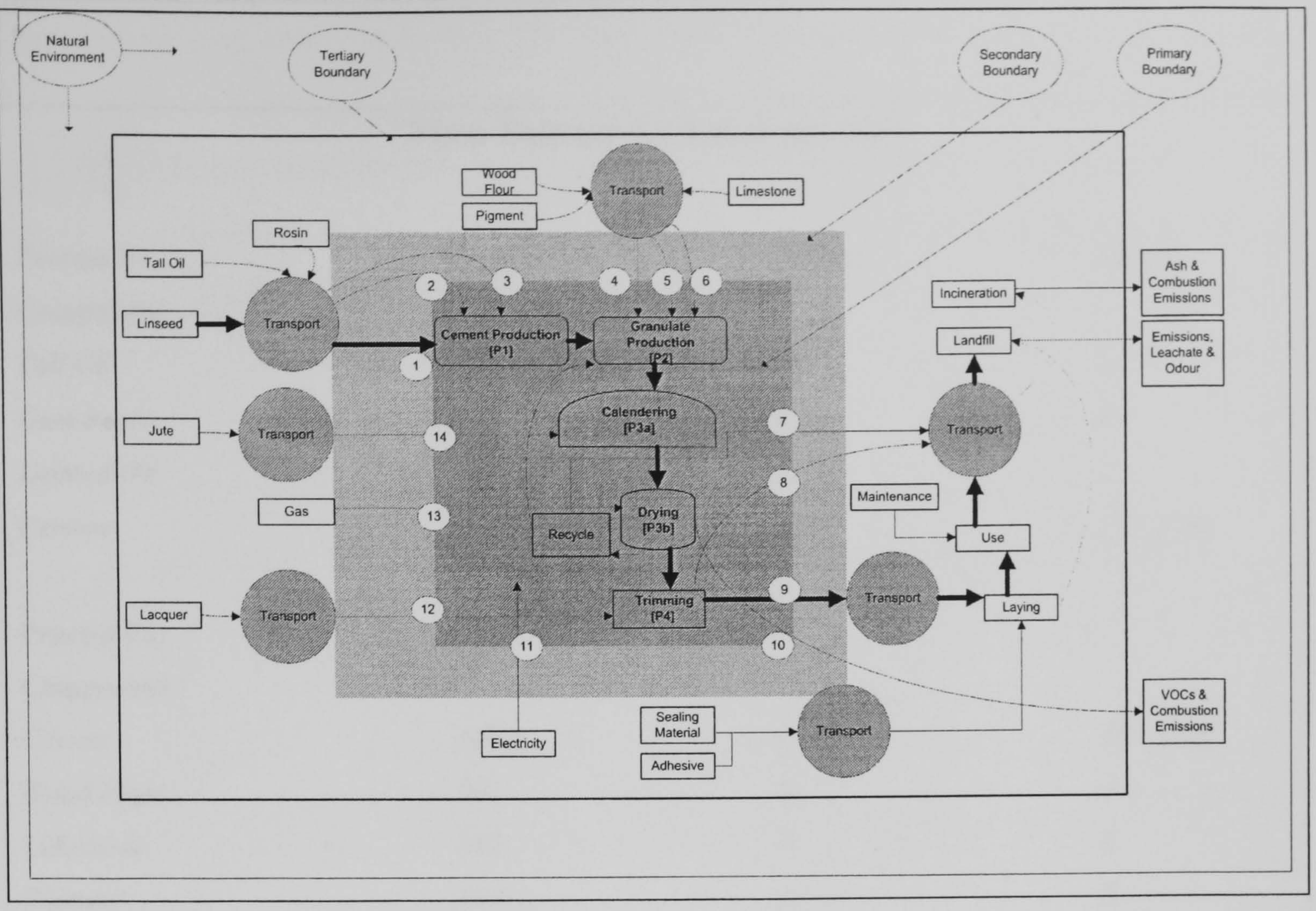


Figure 51 - Boundaries of Operational Control for Linoleum Manufacturer

Mass Balance for Linoleum (kg)

Process P1	**Input**	**Output**	**Stream**
Component			
Tall Oil	*398*	*0*	*2*
Gum Rosin	*76*	*0*	*3*
Linseed Oil	*588*	*0*	*1*
Cement	*0*	*1062*	*[P1_Out]*
Process P2			
Component			
Cement	*1062*	*0*	*[P1_Out]*
Wood Flour	*901*	*0*	*4*
Limestone	*592*	*0*	*6*
Pigment	*101*	*0*	*5*
Granulate	*0*	*2656*	*[P2_Out]*
Process P3			
Component			
Jute	*233*	*0*	*14*
Granulate	*2656*	*0*	*[P2_Out]*
Wet Linoleum	*0*	*2889*	*[P3A_Out]*
VOCs & waste	*0*	*1*	*10*
Process P4			
Component			
Linoleum	*2888*	*2900*	*9*
Lacquer	*12*	*0*	*12*

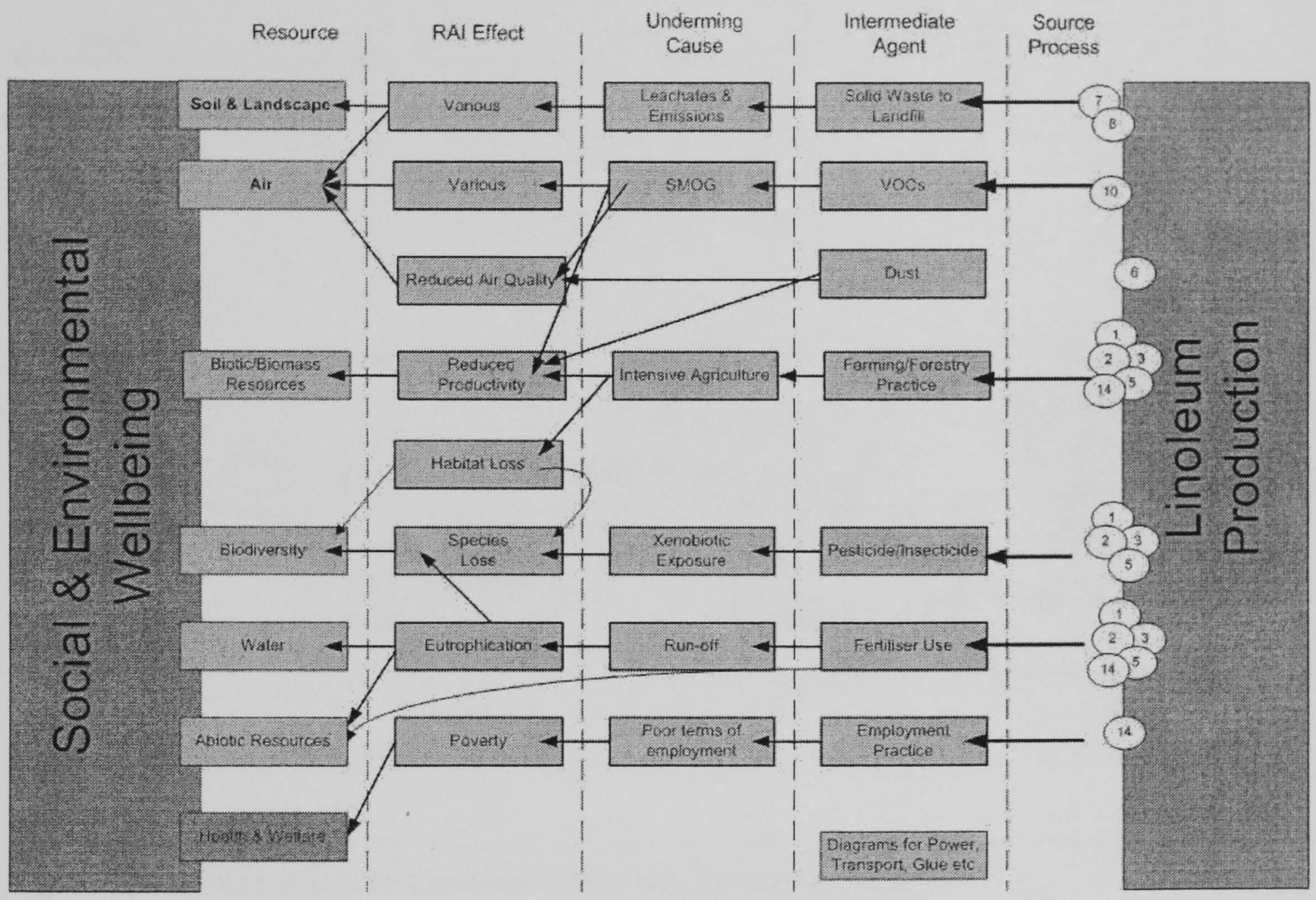
Note: all flows kg normalised as per functional unit.

Data source: Gorrée *et al*

Figure 52 - Mass Balance for Linoleum

9.2.3 Impact Assessment

Fundamental to LCATS impact assessment is construction of the RAIL diagram(s). A master RAIL diagram is shown in Figure 53 and this will become more complex with increased data availability and successive iterations of the LCATS process. The diagram includes a placeholder for subsidiary RAIL diagrams of the utilities: electricity production, gas, and transport. A life cycle flow diagram and associated RAIL diagram for gas-based power generation are shown in Figure 54 and Figure 55 to illustrate the RAIs associated with electricity. Further such diagrams would have to be set up for coal-based power, the other major Netherlands power source, and for nuclear power, since the Netherlands is a net importer of power from other countries including France.



See Figure 55 for RAIL for power generation based on gas. Further diagrams need to be drawn up for other sources of electricity in the grid mix, and also for transport (hence the placeholder in the diagram). Note that more information is needed in order to set up RAIL diagrams for glue, sealant etc. Note also that poverty is a resultant effect of what has gone before it and lessens the availability of welfare. Other welfare RAIs may well exist; this is an area for future work (see page 243).

Figure 53 - RAIL Diagram for Linoleum

The source process streams are identified with the streams entering or leaving the primary boundary as numbered in Figure 51. Such streams inherit all upstream and downstream RAIs external to the primary boundary.

The next step in the procedure is to set up the impact and improvement profile summarising the RAIs together with an estimate of risk as shown in Figure 56 (see page

185 for setting up the impact and improvement profile). This would need to be repeated separately for ancillary RAIL diagrams, and as such gas, transport and electricity do not feature in Figure 56. The figure is updated with the actions to be taken as the RAILs are analysed for elimination and mitigation (see later Figure 61).

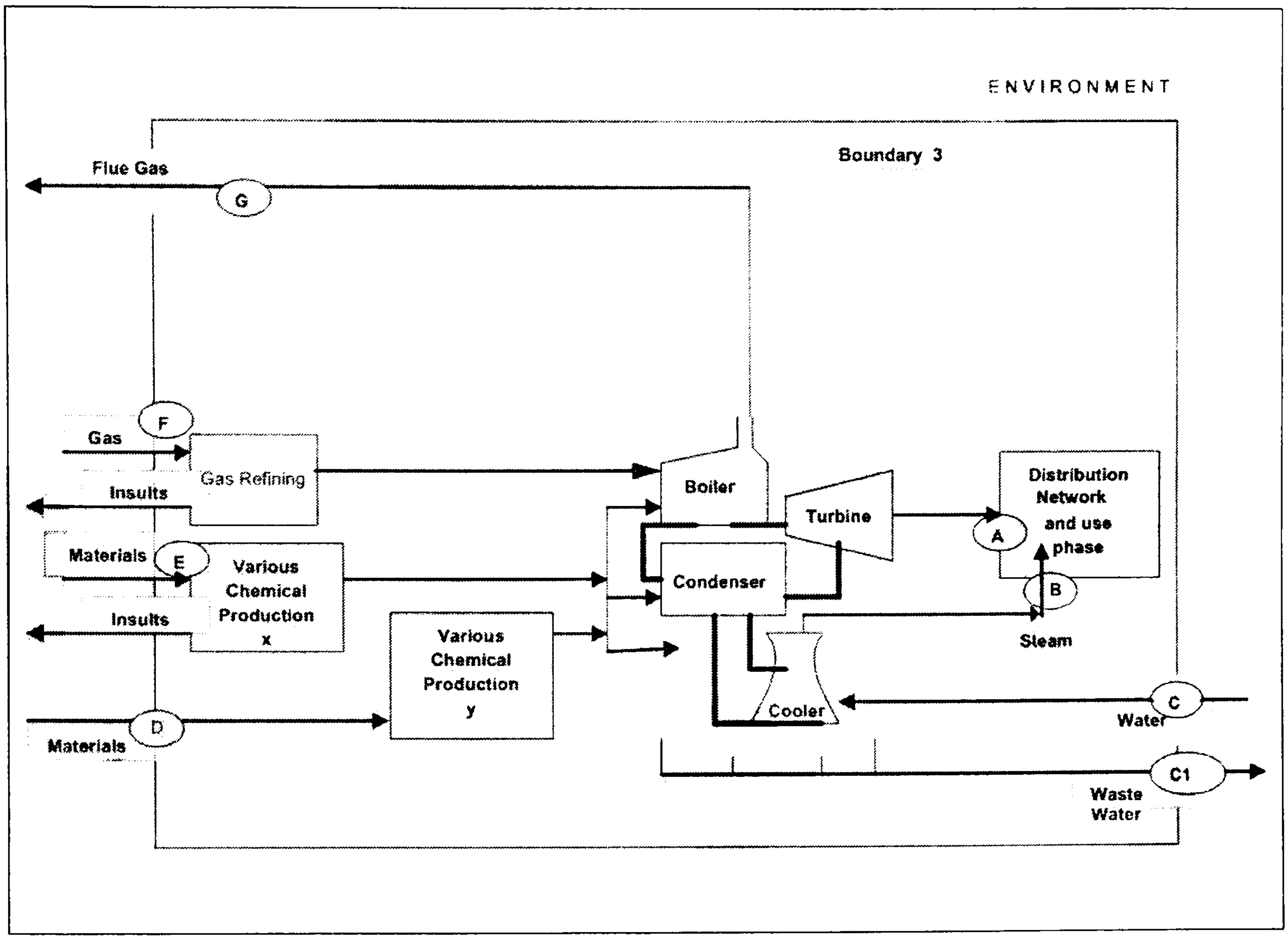
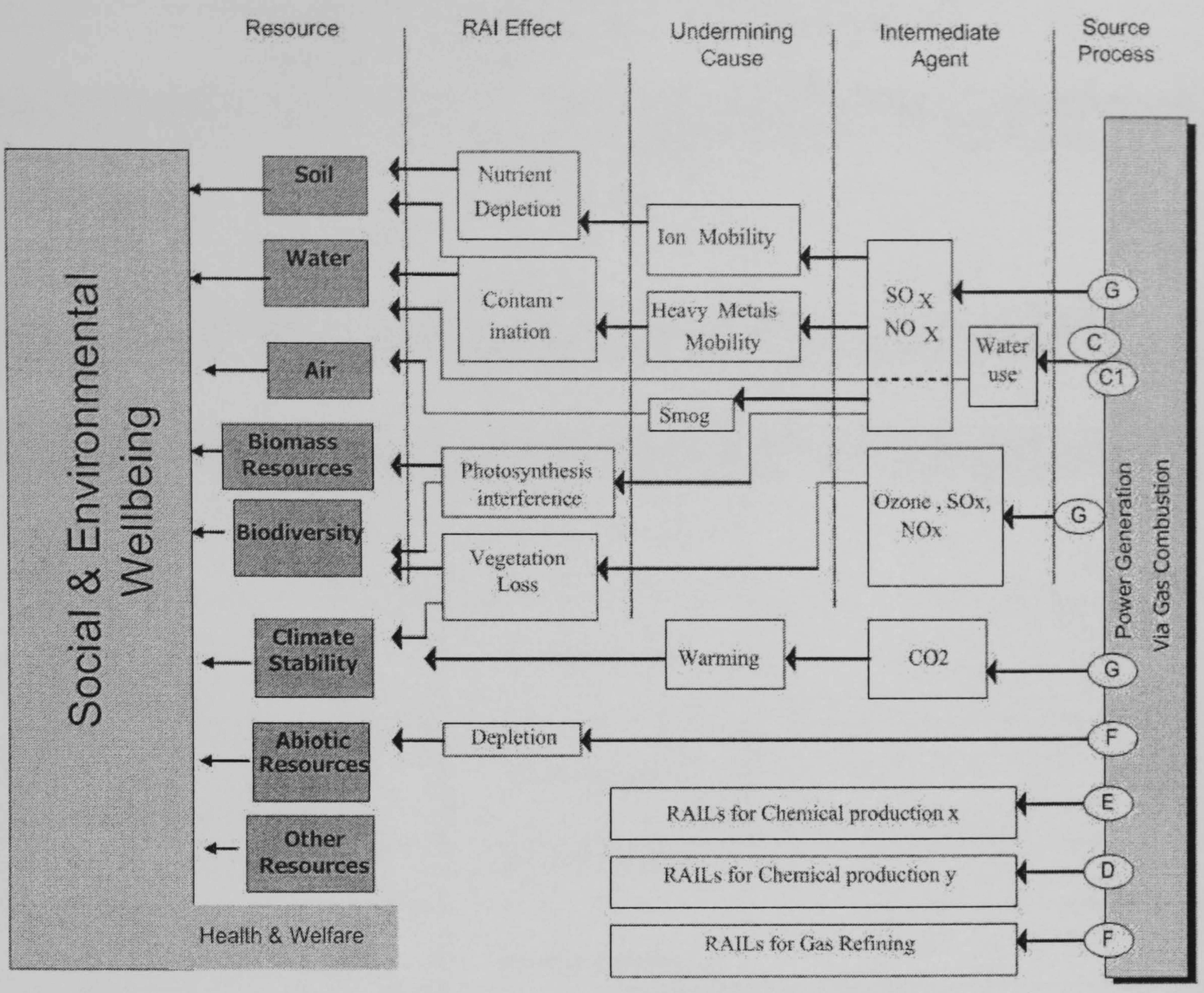


Figure 54 - Flow Diagram for Gas-based Electricity Generation (CHP)

The final (optional) step in the impact assessment stage is to assign numerical indicators to the impact and improvement profile if required for the purpose of target setting for example. Most likely mitigation measures such as efficiency in material use or abatement can also be addressed this way.



Note that this RAIL is essentially the same as Figure 42 on page 183 as used during the brewery example, even though the boundaries of operational control were different (c/f Figure 41 and Figure 54). This servers to illustrate that generic RAIL diagrams could be drawn up for common processes, activities or infrastructure. Note in this diagram, there are no welfare issues identified within the first operational boundary. There maybe welfare issues – and other effects – associated with the chemical production and gas refining in the secondary and tertiary boundaries (note the placeholders for these diagrams in the figure above).

Figure 55 - RAIL Diagram for Gas-based Electricity Generation (CHP)

Impact and Improvement Profile for Linoleum Production			
RAI Link	Priority Effect/Risk	Processing to be Influenced	Nature of Action
Primary Boundary Effects			
7, 8. **Landfill of Waste** Soil/landscape; air; water	Low	[P4] Trimming (and wider site waste in general)	
10. VOC and gas combustion emissions	Low / Medium	[P3b] Drying	
Secondary Boundary Effects			
N/A	N/A	N/A	
Tertiary Boundary Effects			
1 – **Linseed Oil** Biomass; Biodiversity; Water; abiotic resource	HIGH	[P1] Cement Production	
2 – **Rosin** Biomass; Biodiversity; Water; abiotic resource	LOW	Cement Production	
3 – **Tall Oil** Biomass; Biodiversity; Water; abiotic resource	LOW	Cement Production	
4 – **Pigment**	HIGH ?	Granulate Production	
5 – **Limestone** Air; Biomass	LOW	Granulate Production	
6 – **Wood Flour** Biomass; Biodiversity; Water; abiotic resource	LOW	Granulate Production	
8. - **Landfill of Waste** Soil/landscape; air; water	LOW	[P4] Trimming (and wider site waste in general)	
9 -**Landfill/ Incineration of Waste**	HIGH	Use	
12. **Lacquer**	MED	[P4] Trimming	
14. **Jute** Biomass; Biodiversity; Water; abiotic resource	HIGH ?	[P3a] Calendaring	
15. **Sealing Material**	HIGH?	Use	
16. **Adhesive**	HIGH?	Use	

Figure 56 - Impact and Improvement Profile for Linoleum Production

9.2.4 Improvement Assessment

The objective of improvement assessment is to define a path or paths for the achievement of sustainable systems. This means ultimately eliminating all RAILs associated with the linoleum life cycle. In practical terms, since this will not be possible 'overnight' measures to also mitigate RAILs wherever possible have to be sought. Both approaches are necessary since there may be technical, political or economic reasons why a preferred solution cannot be implemented initially.

A cursory examination of the linoleum life cycle shows certain hotspots and impacts. These include to transport and energy use, VOC emissions, intensive farming practice and associated fertiliser and pesticide use. Forbo-Krommenie B. V. clearly take corporate social responsibility seriously [497], but since there has been no mention of a 'fair trade' programme by Gorrée *et al*, it is assumed that there might be welfare issues associated with the acquisition of jute and rosin from India and Indonesia[498] (for this discussion). Unsustainable energy and transport infrastructure common to many if not most manufacturing life cycles are further key issues for the sustainability of the linoleum system. As the situation currently stands, obvious immediate improvements that the business might wish to make relate to material and energy efficiency in general. Other measures are likely to require re-drawing the boundaries of operational influence to realise the potential of affecting behaviour in the supply side for example.

The following pages examine improvements options generated using LCATS improvement strategies and procedures as discussed in the previous chapter (see page 186 onwards, including Figure 46).

9.2.4.1 Primary Boundary Improvement Options (direct operational control)

The improvement assessment begins by examining potential improvements within the *direct control* of the company. Let us start **by examining input/output streams directly crossing or interacting with the primary with the natural and social environment**. Streams (7) and (8) - landfill of waste (see Figure 53) are likely to be relatively small since the bulk of trimming-waste is recycled directly back into the main product. Nevertheless, options for reducing/eliminating the level of waste should be examined. Stream (10) is VOC and gas combustion emissions to the environment. The RAIL issues that this might cause are related directly to both the volume and composition of these releases. Some VOCs are relatively harmless, others can cause significant harm including carcinogenic effects, while all VOCs contribute to the production of low-level ozone. Composition data would be useful, and reduction/elimination at source would be better than reliance on retrofit abatement technology.

Thus far, two source processes have been identified that have direct inputs and outputs to the environment that have associated RAILs namely drying [P3B] and trimming [P4]. Since the streams concerned are wastes and emissions contributing to RAIs, the ultimate course of action would be to remove these altogether, mitigation is desirable, but cannot eliminate the RAIL.

Other streams crossing the primary boundary actually go through other processes mostly outside company control, before interacting with the environment. So for example stream 1 involves transport and linseed oil production which have their own impacts. Note that many issues are revisited as we move through the boundaries, so some repetition is unavoidable.

Continuing to deal with the primary boundary, the next step is to work through the strategies (Figure 46). The purpose of this is to stimulate ideas for ways in which to tackle the processes that directly contribute to the RAILs concerned.

Primary Boundary - Conservation – Seeking Material and Energy Efficiency

1. *Seeking material and energy efficiency.* Reduced trimming-waste and breakage would presumably attract less energy use and costs – were this possible – and prevent some waste to landfill [mitigation]. There may be scope for energy efficiency in the sense of efficient use of gas and electricity [mitigation]. Depending upon the technical nature of the heating in the drying hall, there may also be potential for energy recovery from the drying process using a heat pump [mitigation]. Better use of natural light in site buildings could help reduce electricity use [mitigation].
2. *Service rather than products.* This does not seem applicable at this stage.
3. *Appropriate Application.* This does not seem applicable at this stage.

4. *Quality not Quantity.* Linoleum is already a superior product, both in terms of its environmental profile and its being fit for purpose. This does not seem applicable at this stage.
5. *Use Locally.* A range of renewable energy technologies such as wind turbines, roof-top photovoltaic panels or solar water heaters can offset site energy requirements such as grid-based power [mitigation].

Primary Boundary - Conservation - Minimising Damage

1. *Product Stewardship.* This does not seem applicable here.
2. *Seek Zero Emissions.* There is a possibility of waste heat recovery from the drying stage reducing energy use elsewhere [mitigation]. The lacquering process uses a water-based lacquer [499] – if the lacquer is not benign, it may be possible to reduce airborne emissions through a different technology – a power-based process for example [mitigation/elimination]. It may be possible to reduce the amount of waste going to landfill by better segregation at source – perhaps some waste can be composted [mitigation]. Bringing distribution of the final product under direct control of the company would allow the use of alternative *transitional* transport technology[§§] (for example hybrid vehicles) or fuel (LPG for example) reducing many emissions associated with combustion of petrol or diesel [500] [mitigation]. The use of biodiesel/petroleum blends may also reduce or eliminate many key emissions associated with petrol or diesel [501], but biofuels have the drawback that the land area required to grow feedstock crops is vast and fuel production processes can themselves be energy intensive [502] [mitigation]. It is perhaps inevitable that there will be little influence over container shipment to the United States (a key market).
3. *Principle of Precautionary Action.* It is therefore important to find out more the composition of the lacquer and/or seek alternative lacquering process as discussed in point 2 above. It is important to learn more about the composition

§§ i.e. technology that is not itself sustainable, but forms a necessary step toward clean or sustainable technology.

of the VOC emissions and review whether the existing VOC treatment process is adequate [mitigation].
4. *Substitution.* There may be potential for an alternative lacquering process (as discussed in point 2 above).

Primary Boundary - Enhancement – Industrial Ecology

A possibility for on-site renewable power generation would reduce the dependency on fossil and nuclear-based power infrastructure [mitigation]. If changes to the roofing of any of the factory buildings allowing more sunlight to pass through are feasible, this should be considered [mitigation]. Alternatively, a grass roof attracts a number of economic and environmental benefits [503] - although this may not be easy to retrofit [mitigation].

Primary Boundary - Enhancement – Maximal Socio-Economic Utility

1. *Implement Sustainable Power Generation.* There is a range of on-site renewable power generation technologies available that could reduce the requirement for grid-based electricity [mitigation].
2. *Re-use.* This does not seem applicable here.
3. *Remanufacture.* This does not seem applicable here.
4. *Recycling.* This does not seem applicable here.

The procedure now continues by moving on to the secondary boundary (as described on page 187).

9.2.4.2 Secondary Boundary Improvement Options (under company influence)

The secondary boundary currently has no direct inputs and outputs to the environment at the moment, since it has been assumed that selection of all utilities and services (gas, electricity and transport) are contracted out to third party suppliers with little to no influence over them. Even if it were possible to have some on-site renewable energy power generation, there will likely still be need for use of a 'green' power supply (such as Ecotricity in the UK) to supplement on-site generation. Use of such a vetted supplier would bring the operation from the tertiary boundary of 'no influence' within the secondary boundary (where influence *is* exacted). RAILs in the tertiary boundary electricity generation would therefore be mitigated (at the least) or eliminated (at best) [mitigation/elimination]. Impact associated with plant and hardware manufacture are often ignored in LCA studies – there is however nothing preventing its inclusion in LCATS, particularly if *new* capital equipment or buildings are planned.

Transport can also be brought within this boundary and measures taken to reduce the profile of associated RAILs. By selecting a service supplier who is for example committed to fuel efficient engines/vehicles, LPG or perhaps even hybrid vehicles (using batteries in built-up areas) it would be possible to mitigate the RAILs as they stand [mitigation].

In terms of gas, the supplier could be selected on the basis of commitment to environmental progress [mitigation]. Depending upon availability, perhaps biogas could be used [elimination].

The procedure now continues by moving on to the tertiary boundary, considering all cradle-to-grave processes (as described on page 187).

9.2.4.3 Tertiary Boundary Improvement Options (outwith company influence)

The bulk of the direct inputs from and outputs to the environment take place in the tertiary boundary. Key agents – or source processes – of RAILs include:

- Landfill of solids (9).
- Fertiliser use (1,2,3,5,14).
- Farming Practice (1,2,3,5,14).
- Air emissions from VOCs and dust (6,10).
- Possible welfare issues in acquisition of Jute (14).

Other RAILs contributing significantly to the impact profile of Linoleum are associated to combustion – through transport (streams 1, 2, 3, 4, 5, 6, 7, 8, 9, 12, and 14) and electricity production (11) – and radio-nuclides associated with power generation (11). Composition and the possible effects of the lacquer, pigment, cleaning materials. sealing materials and adhesives is unknown. The Precautionary Principle applied to these materials means that wide-ranging impact must be assumed until indicated otherwise.

Working through the strategies for the last border then:

Tertiary Boundary - Conservation – Seeking Material and Energy Efficiency – No Operational Influence

1. *Seeking Material and Energy Efficiency.* An obvious potential for efficiency (with less use of natural environment inputs and possibly output) is to recycle EOL Linoleum back into new product *were this technically and operationally feasible* [mitigation]. Such recycling means a change of boundaries and is discussed later (see point 4 on page 213).
2. *Seeking to provide service rather than product.* Leasing Linoleum brings advantage of much better product stewardship throughout its life cycle and provides options for recycling or ensuring that the material is appropriately composted or incinerated with energy recovery [mitigation]. A lease model would also potentially allow for longer life through maintenance and use of *preferred* cleaning products [mitigation/elimination]. Such a model has been adopted by Interface in the US [504]. Bringing the linoleum fitting under the control of the company means that fitting waste could be reduced and recycled directly back into the main product [mitigation] and the *preferred* sealant/ adhesive materials could be applied. Presumably a lease model, or 'supply and fitting' would be more attractive for larger corporate customers, hospitals etc.
3. *Appropriate Application.* The obvious question in this case asks whether Linoleum represents the appropriate flooring for a given situation, to prevent it being prematurely taken up and replaced for example. Product promotion should take this into account [mitigation].
4. *Quality not Quantity.* Linoleum is already a quality and *lasting* product since it is generally replaced for reasons of fashion (or the building changing owner) rather than wear and tear.
5. *Use locally.* Raw materials sourced closer to the point of manufacture might help reduce transport emissions [mitigation]. Similarly if raw materials can be further

processed close to point source this may attract a more efficient transport model per functional unit [mitigation]. Since much of the raw material comes from Canada, and an expanding key market for Linoleum products is in the USA, it may make sense to build a manufacturing plant in the US to break the long transport routes were this feasible [mitigation].

Tertiary Boundary - Conservation – Minimising Damage

1. *Product Stewardship.* There is possibility for use of a lease model as discussed in point (2) above [mitigation].
2. *Seek Zero Emissions.* There is scope for significant improvement here by changing the boundaries of operational influence and control and then making appropriate process alterations. A potential may exist for on-site power generation [mitigation] and/or the selection of a 'green' power supplier who uses renewable energy technology. This option would be moving the electricity generation process into the sphere of influence or under the direct control of the company. This would thereby mitigate or remove the RAIs associated with combustion emissions and nuclear power [mitigation/elimination]. Organic production of constituent raw materials will reduce/remove problems associated with chemical-based fertiliser run-off and xenobiotic materials [mitigation/elimination]. Incineration represents an opportunity for waste *reduction* and energy 'recovery' of EOL product, but attracts its own problems in terms of emissions and ash [mitigation]. Composting of EOL product may be an option in the longer term if appropriate adhesives and maintenance products were used, since linoleum itself is biodegradable.
3. *Precautionary Principle.* There is a need to understand lacquer, adhesive and sealing material lifecycles and associated RAIL profiles. Otherwise, a lack of data means finding better product(s) and supplying linoleum customers as a value-add or loss-leader service, with appropriate follow-up education [mitigation]; or moving toward a supply and maintain or lease model where the company oversees the cleaning and maintenance itself; probably only practicable for corporate customers, hospitals or similar) [mitigation/elimination].
4. *Substitution.* Again, organic production of constituent biotic raw materials may reduce/remove problems associated with chemical-based fertiliser and pesticides

[mitigation/elimination]. Crop management strategies - including intercropping and/or crop rotation and the re-introduction of habitat such as hedgerows – helps maintain fertility, reduce pests, and maintain or increase biodiversity [mitigation/elimination]. Intensive agricultural monocultures are thought to be responsible for a 'devastating' effect on biodiversity through its various practices [505].

Tertiary Boundary - Enhancement – Industrial Ecology

In principle, the lease model seems to best serve the strategy of industrial ecology. Closing material loops, and underpinned by renewable power, the lease model would maintain material 'in good order' for as long as possible. Linoleum as a product is good for a life of some 40 years, but is considered end of life (EOL) at 20 years because fashion or change of ownership causes it to be replaced. This means that the useful life of linoleum has been cut significantly short. If hardening of the product in use or adhesives present significant problems for possibility of recycling or perhaps composting then there is still scope for governance over its final fate. For example, if the EOL product is incinerated, the company can seek to ensure that energy recovery is made [mitigation]. A fuller investigation of options for EOL Linoleum – including different transport technology and fuel scenarios, would be useful to an understanding of preferred options while making the 'transition' to sustainable energy and transport infrastructures [mitigation].

In the case of cleaning material it is possible that – even in the event that a sustainably produced material can be found, the company would have to take greater custody of the use phase in order to ensure that appropriate cleaning material is used. This would in effect mean either providing the cleaning material as a 'value added service,' licensing 'approved' cleaning contractors, or perhaps moving toward a supply and maintain regime or leasing model [mitigation/elimination].

Tertiary Boundary – Enhancement – Maximal Socio-Economic Utility

1. *Sustainable Power Generation.* This has already been covered.

2. *Re-use*. This is not really appropriate here. It is most likely that the product has reached EOL through fashion or change to property circumstances.
3. *Remanufacturing/Re-conditioning*. Good maintenance and recycling are perhaps the only approaches towards extending the useful life of Linoleum. [mitigation].
4. *Recycling*. Where it is possible to recycle EOL Linoleum, this would close material loops and presumably reduce energy requirement in production. Recycling – if feasible – would most likely be achieved through a lease model or take-back scheme. Either approach would extend operational control or influence way beyond current boundaries. Recycling would keep the maximal utility of the material in the technosphere. The alternative is composting which would effectively 'down-cycle' the material and make it available to agriculture or horticulture [mitigation/elimination].

9.2.4.4 Review of Improvement Options

Having identified different improvement options across the life cycle – and the degree or change of operational control needed to affect them – attention must now turn to assessment of the potential improvement options. Some of the options do not require deep analytical appraisal – if they are feasible under current economic constraints, then they can be pursued (see Figure 57). Emphasis should be placed on elimination of RAILs wherever possible since this is the objective. Some 'mitigation' options may require to be modelled to check for potential 'problem shifting' (Figure 58). Finally, some elements still require more data before any further assessment can be made. In particular:-

- Composition of VOC emissions.
- Composition of cleaning and maintenance materials.
- Composition of the lacquer and pigments.
- The nature of the lacquering process with more details on alternative technologies such as a powder-based lacquering process.

If no data is available at all (e.g. for the lacquer and cleaning product), a principle of precautionary action would require that an appropriate alternative is sought as a priority. Improvement options for this first iteration of this linoleum study are summarised in Figure 57 and Figure 58 below.

- ***Mass and energy efficiency savings***. Any opportunities to reduce trimming or fitting-waste can be pursued [mitigation]; similarly further reductions in the use of gas and electricity would be beneficial wherever possible [mitigation]. These options are under direct operational control.
- ***Energy and Transport***. Options include better use of natural light and radiation [mitigation]; use of renewable energy for electricity and lighting (either on-site or supplied) [mitigation/elimination]; use of biogas instead of natural gas (i.e. primarily methane/ethane); potential for energy recovery [mitigation/elimination]; and bringing transport and distribution under control and/or influence of the company allowing adoption of (transitional) alternative fuels and/or technologies [mitigation]. Taken to their full extent, these options could be used to virtually eliminate RAILs associated with electricity and combustion of fossil resources. Some of these options fall under direct operational control, while others will need change of boundary to exert company influence.
- ***Waste***. Options include better segregation of solid waste at source, allowing more recycling and/or waste management options [mitigation]. This falls under direct operational control.
- ***Welfare***. Possibility of sourcing Fair-trade jute and rosin [elimination]. [Implementation will require changes to exert influence]
- ***Agriculture and forestry***. Seek organically produced biotic raw materials and/or those grown under an independently certified regime of sustainable production [mitigation/elimination]. Implementation will require changes in operational control to exert influence.

Figure 57 - Straightforward Improvement Options

Problem-shifting is a 'transitional' phenomenon where an improvement in one area of the life cycle results in a different problem elsewhere. If a given improvement option eliminates a RAIL, there is no need to model for problem-shifting. If an option is an efficiency improvement, then again there is no need to model for problem-shifting. Other improvement options may need to be modelled to ensure that they are really an improvement. For full sustainability, problem-shifting disappears the problems themselves have all been removed.

It would be interesting to examine the use of some form of lease model where the company could promote a long life and the direct what happens to Linoleum during use and disposal, were the lease to last that long. This might help make decisions about possible composting or even recycling of EOL product. Such options are likely to depend on specific factors such as proportion of corporate customers; geographic distribution of customers; practicality of recovering EOL Linoleum through the distribution network; technological practicality of recycling/composting EOL Linoleum and so on.

Depending upon the nature of the supply/demand dynamic for the raw materials, and the possibility to select organic and/or certified suppliers, it may be that the only way to mitigate use of fertiliser and xenobiotic chemicals is to pursue a recycling path. Recycling may prove a particularly difficult improvement option since the lifetime of linoleum flooring can be relatively long; a large customer market for linoleum is in the USA; and EOL product may present a range of adhesives which may be difficult to tackle. If recycling is unfeasible, it would be advantageous to see that the product is composted or *incinerated with energy recovery.* Again this is probably best achieved through product stewardship of some kind where a lease model is perhaps the key.

Finally, given that linseed oil comes from Canada and a large market for linoleum in the USA, the corporate feasibility of a linoleum production plant on the North America continent should be examined as reduction in the emissions associated with transport of linseed oil to the Netherlands *and* the transport of linoleum product back to the USA may lower transport use for the lifecycle as a whole.

Figure 58 - Improvement Options Requiring Analytical Modelling

Figure 59 represents an updated flow diagram for Linoleum with changed boundaries of influence, showing how some of the identified improvement options could be implemented (*cf.* Figure 50), while Figure 60 shows the corresponding updated RAIL diagram (*cf.* Figure 53).

In Figure 59 boundaries of operational control and influence have been moved to show how the change could positively effect the lifecycle. Were Forbo-Krommenie B. V. to carry out the linoleum fitting themselves using appropriate adhesives and sealer, a take-back scheme resulting in recycling or composting may then be possible. If the company could also take ownership of maintenance somehow, preferred maintenance materials would also be used. The fitting waste now has the potential to be recycled back into virgin product, rather than going to landfill. Figure 59 also shows linseed oil brought under operational influence by the selection of a supplier of *organic* product, sourced from farms that use intercropping methods, encourage hedgerows and so on. Accordingly, RAI links associated with stream (1) are removed from the RAIL diagram, by freeing farming from unsustainable fertiliser and pesticide effects. Finally, notice that that Rosin and Jute production – through the use of a fair trade program - have been brought under the 'influence' boundary. Accordingly, the RAIL links for jute and gum rosin to welfare in the RAIL diagram have been removed to illustrate *confirmed* positive welfare of Jute farmers/weavers and of the gum rosin producers. This is not to say that there are *no* welfare affects associated with the life cycle – just no known or suspected impacts at this time.

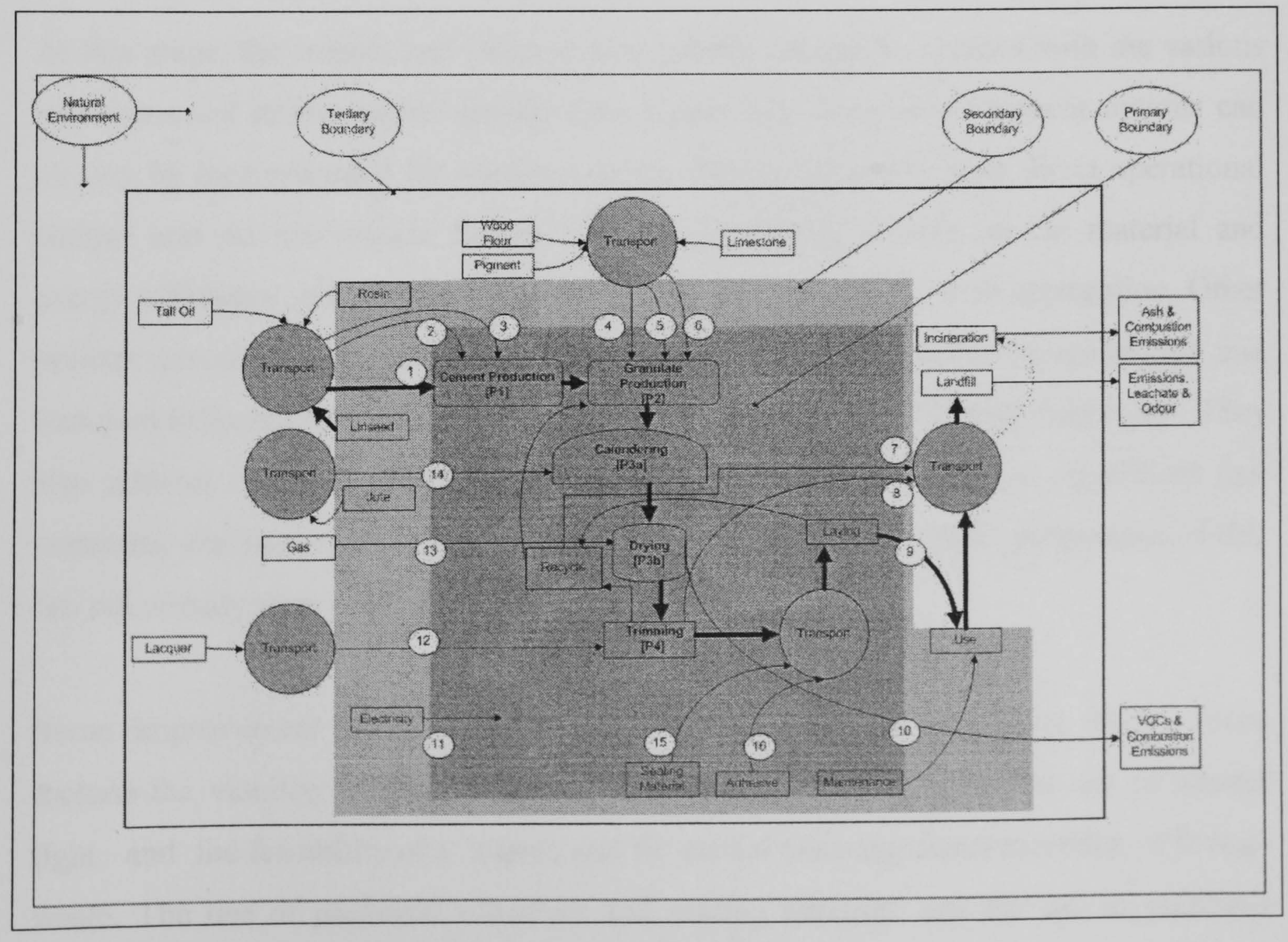


Figure 59 - Updated Flow Diagram for Linoleum Production

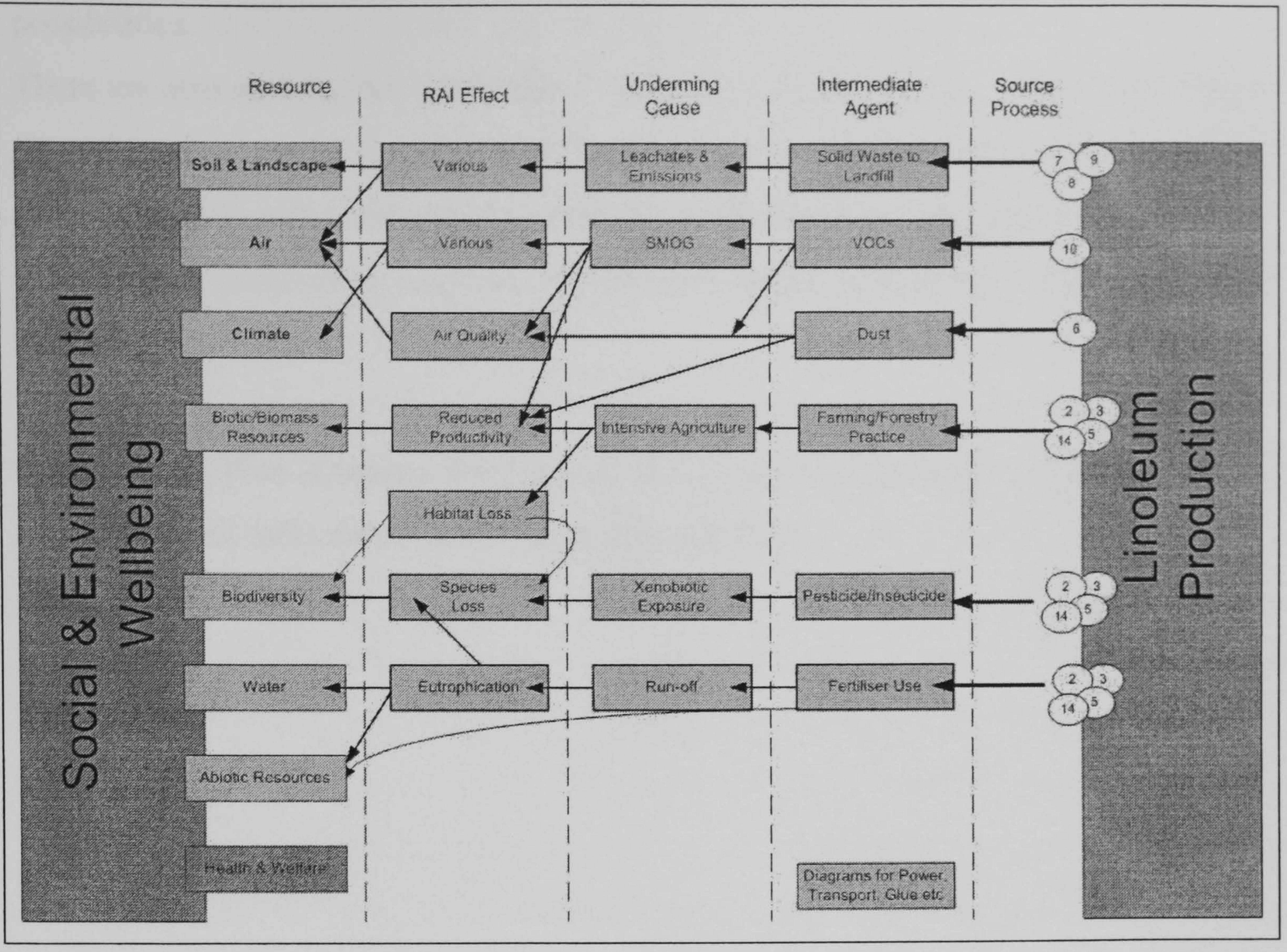


Figure 60 - Updated RAIL Diagram for Linoleum Production

At this stage, the impact and improvement profile should be updated with the various *unconstrained* improvement options (see Figure 61). Some improvement options can already be recommended for *implementation.* Options that are under direct operational control and do not require further data and modelling include on-site material and energy efficiency gains; waste reduction at source; and better waste segregation. Other options not under direct control of the company, will positively influence energy and transport infrastructures which are central issues in the current 'sustainability gap'. They also address unsustainability through seeking the supply of organic constituent raw materials; and the acquisition of Jute and Rosin through a 'fair trade' programme, if this has not already been implemented.

Some improvement options can also be recommended for *feasibility* study. These include the viability of on-site renewable energy generation, the better use of natural light, and the feasibility of a 'supply and fit' model allowing direct recycling of fitting-waste. The use of preferred adhesives and sealing material, and the use of preferred maintenance materials through some form of lease or maintenance contract are other possibilities.

There are also options that need further data and/or modelling – as described in Figure 58 – and cannot yet be recommended for implementation. The feasibility and modelling of these options will be based on information particular to the company, for example the likelihood of influencing suppliers, distribution patterns, feasibility of leasing models and so on.

Finally, more data is needed for pigment, sealing materials, adhesive and maintenance materials – this information should be sought post-haste.

Impact and Improvement Profile for Linoleum Production			
RAI Link	**Priority Effect/Risk**	**Processing to be Influenced**	**Nature of Action**
Primary Boundary Effects			
7. **Landfill of Waste** Soil/landscape; air; water	Low	[P4] Trimming (and wider site waste in general)	Waste reduction at source; better segregation of waste to allow recycling/composting etc.
10. VOC and gas combustion emissions	Low / Medium	[P3b] Drying	Energy recovery if possible; use less gas; get more data on VOC emissions; improve VOC abatement.
Secondary Boundary Effects			
N/A	N/A	N/A	N/A
Tertiary Boundary Effects			
1 – **Linseed Oil** Biomass; Biodiversity; Water; abiotic resource	HIGH	[P1] Cement Production	Acquire organically grown material and preferably from a supplier encouraging use of crop rotation, hedgerows etc.
2 – **Rosin** Biomass; Biodiversity; Water; abiotic resource	LOW	Cement Production	Acquire material from organically grown trees and a supplier committed to encouraging natural diversity.
3 – **Tall Oil** Biomass; Biodiversity; Water; abiotic resource	LOW	Cement Production	Source tall oil from supplier committed to sustainable development.
4 – **Pigment**	HIGH ?	Granulate Production	More data required.
5 – **Limestone** Air; Biomass	LOW	Granulate Production	Improved management and handling to prevent airborne dust.
6 – **Wood Flour** Biomass; Biodiversity; Water; abiotic resource	LOW	Granulate Production	Acquire material from organically grown trees and a supplier committed to encouraging natural diversity.
8. - **Landfill of Waste** Soil/landscape; air; water	LOW	[P4] Trimming (and wider site waste in general)	Waste reduction at source; better segregation of waste to allow wider range of handling options (inc recycling; composting).
9 -**Landfill/ Incineration of Waste**	HIGH	Use	Potential for lease model for corporate customers, allowing recycling of laying waste back into product.
12. **Lacquer**	MED	[P4] Trimming	More data required. Possibility for alternative lacquering technology (e.g. powder-based).
14. **Jute** Biomass; Biodiversity; Water; abiotic resource	HIGH ?	[P3a] Calendaring	More data required – possibility to source Jute from a 'fair trade' style programme.
15. **Sealing Material**	HIGH?	Use	More data required.
16. **Adhesive**	HIGH?	Use	More data required.

Figure 61 - Updated Impact and Improvement Profile for Linoleum Production

9.2.5 Implementation

It is at this stage of the analysis that economic and pragmatic filters are re-applied to the likely improvement options. Some options may effectively be 'taken off-line' at this stage, i.e. they will need to wait until such times as economic or legislative change is favourable or allows competitive advantage.

On the basis of the analysis thus far, any means to implement material and energy efficiency saving should be sought and delivered. It would certainly appear that externally *influencing* energy and transport would be an approach that could have great benefits in terms of sustainability of the overall life cycle of Linoleum pertinent to the company – available options should be reviewed as a priority.

It may be possible to find economic means to 'reward' more sustainable practice that will enable implementation of other improvement options. For example, it may be possible to own or at least influence the use phase of large corporate customers by offering either (1) supply and fitting with twelve months guarantee or (2) guarantee of five years subject to maintenance contract.

Other key recommendations to be followed up immediately include:

- Making a feasibility study of onsite power generation, e.g. wind turbine in partnership with a green energy supplier.
- Seeking suppliers of organic linseed oil feedstock (this is likely to cost more).
- Questioning suppliers of jute and gum rosin about welfare of its producers.
- Seeking missing information as soon as possible.
- Examining a lease model in further detail including the possibility of recycling or composting EOL Linoleum or evaluating wider producer responsibility schemes.

9.3 Merits and Constraints of LCATS Methodology

There are obvious differences and some more subtle differences between the methodological approach taken using LCATS and the more classical detailed LCA approach (as taken by Gorrée *et al* in the Linoleum study). In general, the most obvious difference is the reduced level of complexity of data used in LCATS. There are other differences and these are considered through a closer examination of results and methodological approaches below.

9.3.1 LCATS and Classical LCA for Linoleum - Results

9.3.1.1 LCA as Applied to Linoleum by Gorrée et al

LCA as applied to Linoleum by Gorrée *et al* sought to gain insight into [506]:

- "the environmental impact of Linoleum floor coverings;
- the effects of different processes in the life cycle chain on the environmental impact of linoleum floor covering;
- identifying possible improvements;
- the effects of choices in methods and data on the outcomes."

While not being used for comparison outside the study, Gorrée *et al* have closely followed ISO standardised methodology such that future comparisons will be possible. The approach has been to contrast the lifecycles of three products and various scenarios within these products with a baseline study of 2.5mm gauge Linoleum. The impact assessment is problem-orientated using the usual list of impact categories. Gorrée *et al* found that the primary contributing processes to the environmental impacts which they defined, were growing of linseed (through use of chemical agents); energy and transport use; incineration of linoleum and the use of coal/oil in maintenance and detergent materials.

Gorrée *et al* have used both examination of scenarios and contribution analysis (also known as dominance analysis – see page 122) as the basis for interpreting results and improvement option generation. Main processes contributing the environment impact of the linoleum system were found to be [507]:

- Growing of linseed (i.e. fertiliser and pesticide use).
- Gas and electricity use on-site.
- Transport of raw materials.
- Incineration of linoleum.

- Oil / coal used in maintenance products and detergents .

Their concluding remarks and improvement options include [508]:

- Using linseed that is cultivated with less fertilisers and less pesticides.
- Saving on the use of electricity and gas.
- Recommended further study of pigments
- That 2.0mm gauge linoleum has better environmental performance than the 2.5mm gauge product.
- The continued inclusion of tall oil mixer is preferable to the use of pure linseed oil.
- Reducing the use of gas in drying of cork produces better results for 'abiotic depletion' and 'odour' for cork linoleum.

Other key remarks include [509]:

- "It is apparent that 'production of raw materials' is the main contributor for most categories".
- "The contribution of the disposal phase is negative for most impact categories, except for human toxicity and terrestrial ecotoxicity. This is due to the 'avoided emissions', caused by the production of useful heat when the linoleum is incinerated which is then used for electricity production."

Gorrée *et al* have made a study of the linoleum life cycle using standardised ISO methodology, with results consistent with the objectives of the study. Proprietary data from both Forbo-Krommenie B. V. and other datasets has been employed, and the study carried out using software developed at CML. Formal allocation methodology has been applied. Results and conclusions are based on various scenarios, with interpretation using contribution and perturbation analysis. Attention has been given to missing data and its potential effect and the influence of different impact assessment methodologies has been assessed. Better data to minimise the risk of influence of wrong assumptions on results has been advocated, and advice on data necessary for future studies on linoleum offered. This has been a detailed analysis of life cycle linoleum commissioned by Forbo-Krommenie B. V., resulting in a number of suggested improvements as shown above.

9.3.1.2 LCATS Applied to Linoleum

LCATS applied to Linoleum has the specific objective of seeking a *sustainable system* for Linoleum. The study has sought to understand what needs to be done to approach a sustainable system by:

- Understanding and describing current unsustainable features and processes of the Linoleum life cycle.
- Generating a range of options for improvement towards a sustainable system for linoleum.
- Identifying what can be done operationally and what can be done to better influence external scope.
- Highlighting key information that is currently missing.
- Identifying which potential changes need to be modelled.

Linoleum production and use appears to have the potential to be a highly sustainable system. Particular elements that heavily contribute to the current 'sustainability gap' are:

- Fertiliser and pesticide use in raw material acquisition.
- Gas and electricity use at the manufacturing plant.
- Transport of raw materials, and distribution of final product.
- Landfill or incineration of EOL linoleum.

Concluding remarks and improvement options include:

- Suggestions for immediate change include material and energy efficiency across influenceable areas of the system, including but not limited to gas and electricity use; seeking opportunity to positively affect external transport and energy including switching to a 'green' electricity supplier; sourcing produced raw materials from suppliers insisting on good farming practice and organic produce; waste reduction at source; and better waste segregation.

- Suggestions for modelling including the potential for recycling and/or composting EOL linoleum; the potential for lease or 'supply, fit and maintain' models, allowing trimming waste to be recycled and preferred ancillary materials to be employed in fitting and use; and the possible advantage of opening a linoleum manufacturing plant in North America.
- The need for more information on the welfare of jute producers; and of lacquer, pigments, VOC emissions, and maintenance/cleaning materials.

This first iteration of LCATS has given output consistent with the aim of the study. The study has been made using minimal data and with a straightforward methodology. Some 'expert' knowledge has been applied in drawing up the RAIL diagrams. Some elements of the life cycle have not been examined because of availability of data. The study suggests that linoleum can form part of a sustainable system. It has described the key issues currently preventing this and has suggested a range of improvements to close the sustainability gap. Some of these options can be implemented without further assessment – some require more data or modelling.

9.3.1.3 Discussion of Results

Both LCATS and classical LCA studies have reached output or results consistent with their initial objectives. Much of the output does coincide – such as attention to raw material acquisition and energy use – but there are differences however, especially with respect to the suggestions for *improvement* within the life cycle – see Figure 62 below. LCATS has resulted in wider ranging improvement options than the classical LCA and, as a consequence of goal rather than problem-orientation, this is not perhaps surprising. LCATS has sought improvement options as its 'results', but the 'results' of the classical LCA study – like other LCA studies – often refer to the relative contribution of different impacts to the overall life cycle and associated analysis. The relative contribution of impacts may reveal interesting insights and help answer specific questions, but do not generate improvement options *per se*.

LCATS	Classic LCA
• Source supply of organic linseed, cultivated using good farming practice e.g. promoting hedgerows; seek certified wood products etc. • Implement material and energy efficiency wherever possible including reduced gas and electricity use. • Positively affect external transport and energy by switching to a 'green' electricity supplier and haulage using LPG or biodiesel blend; investigate possibility of on-site renewable power. • Take control of fitting where possible to allow recycling of fitting waste and use of preferred adhesive and sealing materials. • Explore options for EOL linoleum such as recycling, incineration or composting. • Waste reduction at source and better waste segregation. • Seek 'fair-trade' jute and rosin (if this is not already the case).	• Use linseed cultivated with less fertiliser and pesticide. • Reduce gas and electricity use. • 2.0mm gauge linoleum has better environmental performance than 2.5mm gauge. • Linoleum with tall oil has better environmental performance than Linoleum without tall oil. • Cork linoleum has better results in most chosen categories than the baseline product.

Figure 62 - LCA and LCATS Improvement Options for Linoleum

The LCATS output should not be considered 'better' or 'worse' than the results reached by Gorrée *et al*: the differences are due to differences in the objectives, perspective and methodology used in the study. The differences in approach are examined further below.

9.3.2 Comparison of Classical LCA and LCATS Approaches

The literature often follows the development of the classic analytical, decision-support style of LCA as standardised by ISO, and which is applied by Gorrée *et al* in their study of the Linoleum life cycle. Classic LCA demands rigorous methodological elements to prevent 'abuse' or misinterpretation during scenario analysis or comparisons that are often its goal. Frankl and Rubik observe [510]:

> "The ISO standards 14040 and 14041 contain a lot of prescriptions about what should be done in which way. In particular, there are strong

requirements if the results of LCA are intended to be communicated to any third party. However, this ISO-definition encompasses a part of different life cycle approaches only."

LCATS is intended to appeal to new life cycle audiences by *removing* some of these heavier methodological aspects. Accordingly, LCATS does not suggest that a given lifecycle is 'better' than another, which in any case is a fairly pointless exercise when the attainment of sustainable systems is used as goal.

Figure 63 below summarises a qualitative/qualitative – goal/problem orientated continuum, highlighting the relative positions of LCATS and classic LCA. Streamlined approaches are discussed further below. Classical LCA is located in the quantitative, problem-orientated quadrant of Figure 63. It is quantitative because it seeks to use numerical approaches to analysis wherever possible to enable clear decisions and help maintain certainty. It is problem-orientated through its use of environmental problems within the impact assessment to support decisions on a given matter - for example 'which is greener?' or 'understanding and improving' a given life cycle using scenarios (as in the Gorrée *et al* study). Instead, LCATS has a specific objective of sustainable systems, and uses a more qualitative approach to impact assessment through resource availability infringement analysis that seeks to maintain process-specific information through the use of RAIL diagrams.

LCATS in particular seeks to uncover why a given life cycle is unsustainable, looking at the essence of problems and questioning what needs to change to reach the goal rather than seeking to determine information related to decision-support. This presents a downside to LCATS: it may be difficult in some complex scenarios (for example) to gain sufficient certainty over whether scenario A is better or worse than scenario B. It would, for example, be difficult to examine the possibility of recycling in the Linoleum study without the more rigorous analysis afforded by elements of classical LCA. Similarly, conclusions made by Gorrée *et al* with respect to the continued use of tall oil could not easily be reached by LCATS.

In a sense, LCATS is a simplified methodology, but a full life cycle view is taken and there is no prior targeting of particular environmental concerns. Thus the approach is not streamlined or simplified in the sense of the published methodologies discussed in chapter 6 (see page 108).

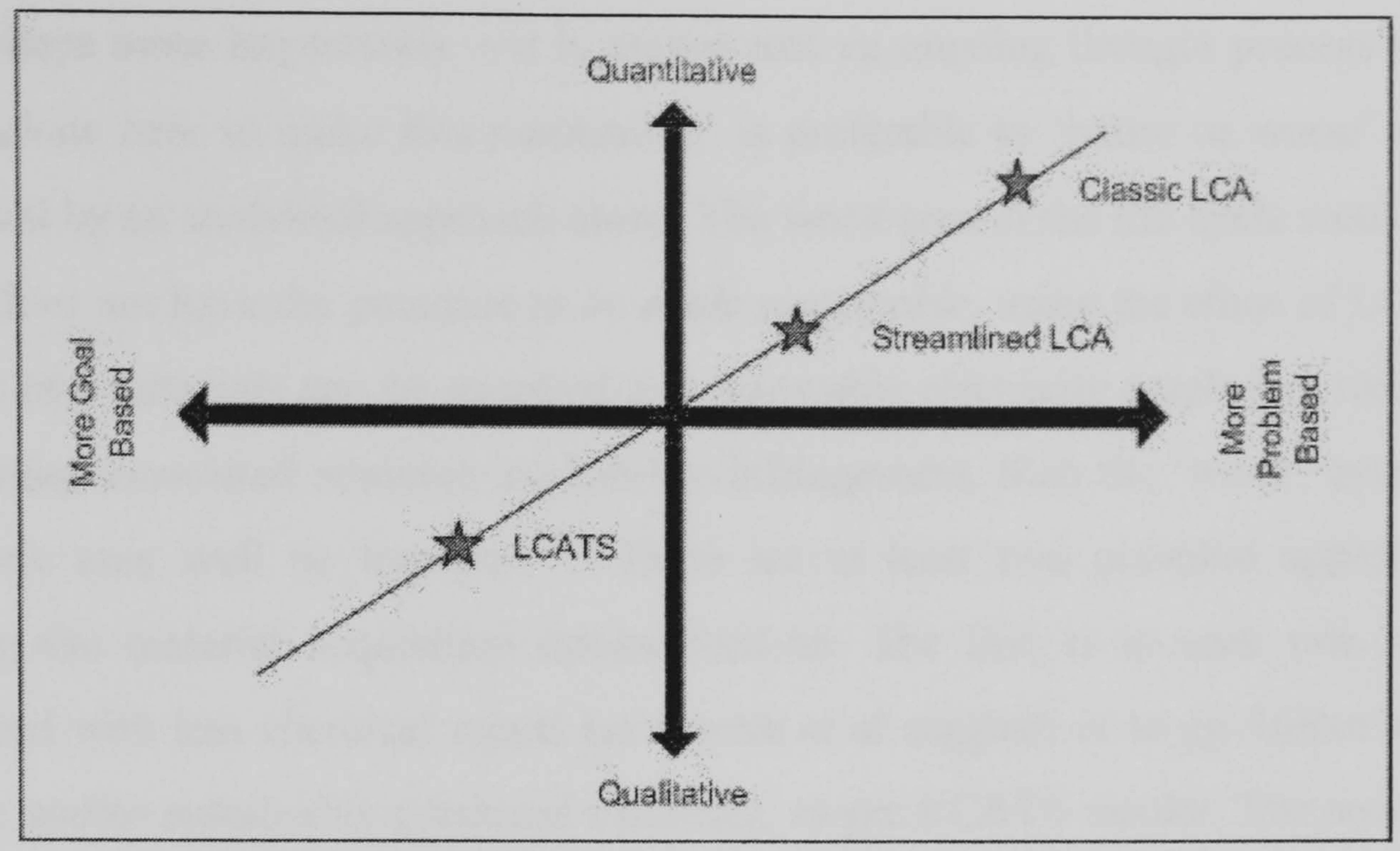


Figure 63 - Relative Approaches of LCATS and Classic LCA

A strength of LCATS is its ability to address all resource availability infringement whether qualitatively or numerically described. Through LCATS unsustainable elements of the life cycle are defined so that options for mitigation or elimination of the unsustainability, expressed as RAIs, can be generated. This does not necessarily demand numerical impact data.

Using purely numerical data, both scenario use and contribution analysis (discussed on page 122 onwards) are useful means of profiling the most problematic areas of the life cycle and gaining insight into problem areas and highlight quick-wins. Here an objective of an 'improved' life cycle is being addressed as opposed to a *sustainable* life cycle sought by LCATS where RAIs are treated as a problem areas to be tackled individually, not traded-off. Contribution analysis has, in the Gorrée *et al* study, shown that – on the basis of impact categories selected – raw material acquisition is the most important because of greatest contribution to all impact categories. In other studies this may not be so clear-cut.

Like the Gorrée *et al* study, LCATS also highlighted the raw material acquisition stage through the resource availability infringement involved but does not consider this stage to be 'worst' area of the life cycle for two reasons. The first is contribution analysis has not been used since there are other qualitatively described problems, for example potential welfare issues, radionuclide effects, and nutrient cycle interruption. Secondly – and perhaps more importantly – it is argued that an ongoing thought process of 'what can be done here to make this sustainable' is preferable to 'better or worse' thinking supported by an analytical approach alone. The worst area of the life cycle would be one which does not have the potential *to be made sustainable,* using the ethos of LCATS. If organic raw materials can be acquired and renewable electricity employed, reducing or eliminating associated resource availability infringement, then the 'worst' areas of the life cycle may well be transport[***]. There are at least two potential approaches to tackling the material acquisition issues head-on. The first is to seek raw materials cultivated with less chemical inputs (as Gorrée *et al* suggest) or to go further and seek organic and/or sustainably produced materials, as per LCATS results. The second is to consider the technical potential for recycling as found by LCATS, but missing from the Gorrée *et al* study. It has been assumed here that the Gorrée *et al* study does not mention the possibility of recycling because 100% incineration has been assumed in one of the scenarios.

Incineration of linoleum is an interesting issue. In Gorrée *et al*'s study it was deemed to be one of the best improvement options contributing to a negative result for disposal across all indicator categories in LCA. It may be that incineration is a more sustainable option for dealing with EOL Linoleum than recycling or landfill, but this conclusion *cannot* be reached on a tactical basis of avoided emissions associated with electricity. Electricity *has* the potential to be generated renewably, and the company *can* look into options for its procurement as discussed. Moreover, incineration of linoleum removes the potential to close a material loop, whether it be as a 'technical' nutrient, i.e. recycled back into linoleum and returned to the economy, or as returned to nature through composting for example. Again, as stressed earlier, there may be problems associated

[***] Taken to its extreme, it may be that a given life cycle is fundamentally unsustainable. For example a core process or material cannot be used sustainably. In this event, tactical effort should be made to close the 'sustainability gap' (see page 193) as far as possible, but to strategically look for a way for the business or organisation to find another way to fulfil its function.

with these latter options, making incineration of linoleum the best way to handle EOL linoleum. The conclusion cannot be however based on avoided electricity emissions when options for green electricity exist.

One of the reasons Gorrée *et al* chose to credit incineration with energy recovery against electricity is perhaps that there has been no suggestion of change to infrastructure, beyond use of less electricity *per se*. Behind LCATS is an ethos of influencing *infrastructure* wherever possible, by encouraging the company to adapt itself to force a more sustainable outcome. A strength of this approach is in the questioning of all areas of the life cycle, and the presumption that influence can be extended to positive effect. Companies must take action to adapt themselves and their life cycles because there is a degree of producer responsibility here and it is not proactive to declare infrastructure some one else's problem.

The discussion of incineration and electricity highlighted differences in conclusions that perhaps have as much to do with differences in perspective when setting study objectives as they have to do with the methodology itself. Difference in perspective can also be found to influence the interpretation of inventory and impact data. Gorrée *et al* advocate better data to minimize the risk of influence of assumptions being wrong on study results [511]. This is true, but is more critical in a study where the analysis seeks to trade-off different improvement options against each other. Consider the following [512]:

> "Forbo-Krommenie B.V. could improve their environmental performance on many impact categories by using linseed that is cultivated with less fertiliser and less pesticides. This seems a more promising option than reducing transportation distances for raw materials".

LCATS encourages that these issues as RAIs be tackled separately, and concurrently making the above improvement suggestions relatively weak. *Organic* produce could eliminate much of the problems associated with fertiliser use and, rather than seek less fertiliser use, allows attention to focus on tackling energy and transport sustainability as well as on reduced transport distances. Trading off fertiliser use against transport emissions does not fit well with an objective of a sustainable system; confidence in certainty over whether scenario *x* is better than *y* is therefore unnecessary. Similarly, Gorrée *et al* have examined different impact assessment methods to 'determine the extent to which the results of the study are influenced by the method of impact assessment used'. Again this is not such an issue once trade-off is out of the question. The best way to tackle uncertainty, as regards the appropriateness of the model, is to systematically remove the RAILs. Where trade-off or comparisons *are* unavoidable, this is where LCATS must of course give way to a more rigorous assessment. For example, were recycling to be a technical possibility, classical LCA through linear programming for example (see page 123) would probably be a good tool for confirming the option and determining the recycling rate.

Another observation about the differences between the LCATS and LCA approaches concerns improvement assessment in general. The driver for the various scenario comparisons and the use of contribution & perturbation analysis in the Gorrée *et al* study appears to have been primarily used to meet the objectives of understanding the environmental impact of – and potential improvements for – the life cycle of linoleum. LCATS has reached many of the same conclusions and has gone further in reaching improvement options whilst using straightforward methodology and without much of the data available to the Gorrée *et al* study. This suggests that either:

1. LCATS is particularly well-suited to relatively simple life cycles, which is more likely to be true of SMEs; or
2. Since linoleum is a relatively simple product, classical LCA as applied has perhaps been an 'overkill'; or
3. LCATS can provide a fairly rapid health-check of an even bigger company or system prior to the use of classical LCA on chosen key elements or scenarios within it.

A combination of the above is true in the case of linoleum. Scenario, contribution and perturbation analysis are useful means of gaining insight into a lifecycle and revealing potential improvements. However, application of specific strategies for the generation of improvement options has proven itself just as valuable in the LCATS study discussed here. One technique cannot really be recommended over the other as each have their own benefits and are actually complementary to each other.

Since LCATS has led to many of the same conclusions as its more complex counterpart *and* has made suggestions for future analysis, a final observation here is that it could be used as a screening tool highlighting pertinent scenarios for examination in a classical LCA application. A more interesting question for linoleum, from a heavier analytical point of view, might be whether a lease model would provide an overall benefit, including the potential for recycling or composting – if technically feasible within the current economic climate. For full sustainability, this is not an issue.

9.5 Discussion

LCATS has drawn pertinent conclusions with a relatively straightforward methodology and – in this application – with limited data. The study suggests that it is well suited to simple systems at the least, since conclusions are not dissimilar to those drawn using a classic LCA approach using ISO standardised methodology. Indeed the application of LCATS has reached a wider range of improvement options through its proactive approach, highlighting potential paths forward toward a sustainable system for linoleum.

This straightforward methodology and proactive approach will attract a new participants in life cycle applications – either SMEs, who are known to avoid LCA, or board-level interest in LCA of larger firms seeking a full sustainability perspective. This is not to say that an SME could perform LCATS as stands as it still needs expert input in terms of RAIL profiling and risk assessment. Furthermore, the desire to have a comprehensive approach has perhaps made this first generation of LCATS less practicable as it could be, particularly surrounding the iterative improvement stage. Future work around these areas is discussed in chapter 10 on page 243. The principle selling points of LCATS for a new audience however remain in helping to plan a course for the achievement of a sustainable system without being overwhelmed with data and methodology.

It is unavoidable that some companies must accept their operation is unsustainable as a whole, after application of LCATS and a resultant better awareness of sustainability. Thus, while they might be able to improve their operation some way, they will not close their sustainability gap. As such, they will need to look at changing their product or portfolio in the longer term, as discussed on in Figure 26 on page 87.

While LCATS has shown a wider potential as a screening LCA, prior to full classical LCA, it is different to existing 'streamlined' LCA methodologies, as it narrows the scope by other means. Figure 64 summarises key differences in the approach commonly taken in detailed LCA with LCATS.

LCATS	Classic LCA
• Goal orientated and strategic • Directly promotes Sustainability • Bespoke methodology, primarily for internal use • Avoids complexity of analysis • Process-orientated impact and improvement assessment • Heavier qualitative component • Seeks widest description of infringement to life support resources • May attract new user group • Likely to create interest and understanding at company board-level	• ISO standards exist • Strong analytical methods • Problem Orientated • Most appropriate way to scenario or life cycle comparison (external comparison possible) • No predefined goal means heavy onus on appropriate goal getting • Aggregates impact data • Defined quantitative category indicators • Complexity puts off potential users • Difficult to influence decision makers towards sustainability beyond process improvement

Figure 64 - Features of LCATS & Classical LCA

Finally LCATS should increase classic LCA use by attracting new and potentially influential business policy audience to the life cycle approach. Through helping to highlight possible paths forward toward a sustainable system, the value in the proactive approach proffered by LCATS cannot be underestimated.

9.6 Conclusions

The main research question for the thesis asked:

> **How should LCA methodology be configured such that it better promotes environmentally sound product systems, and thereby sustainability?**

Life Cycle Assessment Towards Sustainability (LCATS) as presented and appraised in chapters 8 and 9 has answered the main research question through a life cycle approach which:

- Specifically implements an operational goal of a sustainable system for a given life cycle function, helping businesses to plan specific and strategic steps toward a sustainable future.
- Includes impact methodology based upon a broad assessment of unsustainable features of the life cycle, expressed in terms of resource availability, complemented by a broad range of proactive strategies for improvement.
- Can attract a new audience to life cycle assessment through straightforward methodology, and better promotes sustainability by being more appealing to a wider user base - particularly at policy level.

Application of LCATS to a life cycle of Linoleum has reached similar conclusions regarding impact and improvement assessment as another published study, using the same data. Indeed, some results of that study have been challenged through the difference in perspective offered, even though LCATS has used relatively modest methodology and data in comparison (moreover, areas to further improve LCATS to this end have been identified). The goal of sustainable systems has lead to the proposal of more wide-ranging improvement options through LCATS. Specific strategies for moving toward a sustainable system for Linoleum have been presented and the study has also highlighted interesting scenarios for a tighter application of classical LCA. This reveals a possible use of LCATS as a screening tool before setting objectives in a classical LCA (rather than relying on more ad hoc scenario selection).

Thesis Appraisal and Conclusions

Chapter 10 - Thesis Appraisal and Conclusions

10. Objectives

The purpose of this chapter is to appraise the work both in terms of the research question and the implications of the findings.

10.1 Introduction

Part I of this thesis considered the development in understanding of the true nature of the environmental crisis over the last 40 years. A definition of sustainability has been developed, and operationalised for business in terms of a goal of *sustainable systems*. The various ways in which anthropogenic activity is inherently unsustainable have been examined in order to assess the scale and features of the challenge posed. In Part II, the goal and the requirements of sustainable systems was used as a framework within which to review the role and suitability of life cycle assessment as applied toward this objective. Finally, Part III of the thesis developed and appraised the ways in which an LCA-based should be defined to enable businesses chart a course for sustainable systems. This formed the conclusion to the main research question which asked:

> **How should LCA methodology be configured such that it better promotes environmentally sound product systems, and thereby sustainability?**

10.2 The Path Taken in this Research

In an attempt to better understand what might be required of LCA, or at least its 'best purpose', recent milestones of environmental concern were reviewed. This revealed more profound environmental concerns than the LCA literature seemed to acknowledge. Backed by a growing consensus of opinion, these concerns include strong indications that we are already *significantly* undermining life supporting resources and that we are facing an unprecedented environmental crisis. In order to positively pursue the concept of sustainability it was felt that a strategy was required which would characterise the new ethos necessary, if the present unsustainable direction of development was to be changed.

The way in which LCA methods have developed was studied and selected literature was reviewed. This gave a better understanding of the relative strengths and weaknesses of the methodology concerned, which was found to be difficult to use especially for the novice. Despite numerous guidelines and standards being available, the methodology also seemed contradictory or confused. At this stage, the very purpose of LCA began to be questioned.

A further examination of the LCA literature revealed that nowhere did it seem to address the issue of sustainability directly. While initially LCA methodology had appeared to provide general guidelines to meet a wide variety of applications, a closer examination revealed that many methodological elements were in fact specific to a goal of product comparison, even though the methodology was deemed to have general application. The conclusion was that such elements of LCA were confusing, often controversial, and unnecessarily embroidered so that they formed a barrier to deriving full value of LCA in terms of its potential to promote sustainability. Despite LCA already being one of the most appropriate tools available for promoting sustainability in general, it was further concluded that if LCA could *better* promote sustainability if:

- There were a clear and practicable goal of sustainability that could drive LCA application.
- The methodology included an explicit and *strategic* improvement assessment component which helped challenge the *status quo* or provide insight into further options.
- There were simpler methodological approaches *per se*, which would have the additional benefit of attracting a wider audience for LCA.
- Impact assessment, which is the kernel of the LCA procedure, was expressed in terms of sustainability.

LCA as currently employed has arisen out of the need for problem-orientated analytical methods. Nevertheless, it was clear that this was not the proactive and strategic-based general assessment that was necessary to help business chart a course for sustainability and that this was a tool with a heavy emphasis towards decision support. Consequently it was felt that there was an opportunity to create an LCA-based approach which would complement other tools in the environmental management toolkit. This approach would be based on an explicit goal of sustainability with a corresponding tailored and appropriate methodology. The first step towards this was to operationalise sustainability as an objective of *sustainable systems*, and then to examine the relative strengths and weaknesses of problem-based LCA with respect to the requirements of this objective. The results of this review helped shape the requirements needed to define the approach, underlining the development of Life Cycle Assessment Towards Sustainability (LCATS) delivered in Part III of the thesis. The remainder of the research was to review the strengths and weaknesses of the LCATS approach as compared with contemporary LCA methodology.

10.2 Conclusions about the Research Question

The research question to be addressed in this thesis was:

> **How should LCA methodology be configured such that it better promotes environmentally sound product systems, and thereby sustainability?**

Broadly speaking, it seems that current LCA methodology and its application have been shaped by a need for robust decision-support tools under a problem-orientated framework. It also seems that there is a broad consensus that sustainability now represents the ultimate goal and challenge for environmental management. Life cycle assessment is a useful component of a toolkit designed to meet this challenge. LCA can be applied directly toward sustainable outcomes as stands, but interpretations of sustainability within the LCA field seem weak, and LCA methodology maturing as a decision-support tool is not as strong on pro-active and strategic improvement option generation as it might be. Much of the development of impact assessment methodology has been to support a problem-orientated view and decision-support: this may help to address a given formulation or problem but is not necessarily optimal in forming strategy toward sustainable outcomes. Similarly the decision to employ 'interpretation' rather than explore and develop 'improvement assessment' has on the one hand helped standardise the LCA tool, but diluted the potential to promote sustainable means to the full. The inclusion of economics in the analysis has taken LCA nearer a decision-*making* rather than a decision-*support* tool; this is however at the risk of falling back to a BATNEEC approach (which antagonises effort toward a sustainable outcome). There is consensus that LCA should be used more to plan ahead in 'prospective' mode – a significant development. Finally, there is the issue that LCA complexity has clearly put off some potential users, particularly small to medium sized enterprises (SMEs). Something which is regrettable since SMEs represent the lion's share of businesses today. Furthermore, complexity of method has led to the demand for 'streamlined' LCA methods – many of which are counterproductive, especially from the sustainability viewpoint.

It is concluded then, that since it is goal definition that ultimately sets LCA methodology in a typical problem-orientated and detailed study, care is taken to ensure that this goal is pertinent to sustainability and - critically - that the prerequisites for sustainability are well understood. Sustainability as described in the lifecycle literature is often weak and there appears to be a dangerous presumption that application of LCA somehow *implies* sustainable development (over-use of comparative LCA illustrates this point). This thesis has presented an understanding of sustainability built from first principles and reinstating the environment as the fundamental constraint of the environment, social and economic domains. An objective of 'sustainable systems' has been developed as an operational goal – a more motivating and less daunting challenge – supported by a concept developed here of 'resource availability infringement'. This has been used as the explicit goal and basis for LCATS as developed and appraised.

Care in goal definition is particularly important if sustainability is to become a new raison d'etre for life cycle tools in general. It is recommended that a strategic and conceptual improvement assessment is applied as a best practice, rather than relying solely on numerical interpretation techniques such as dominance analysis (sustainability cannot be delivered by eco-efficiency measures alone). There remains room for development of simpler life cycle methods, but on the proviso that the full life cycle view is not compromised. To this end, this thesis presents an approach that has proven highly effective with straightforward methodology and modest data, by employing a predefined goal of sustainable systems, qualitative impact assessment based on resource availability and a strategic improvement methodology. The approach is intended to encourage wider take up of LCA and life cycle thinking in general – particularly by, but not limited to, SMEs. This alternative to classical approaches helps businesses to *plan a course* toward a sustainable system and is achieved not only by being more prescriptive both in terms of goal and 'what to do' but also by leaving out much of the complexity of the more detailed classic LCA method. As stands, an SME would still need some support performing LCATS since the RAIL concept needs further development – this is discussed further in future work.

Further conclusions that are drawn from this work:

- The pursuit of sustainability can and should be adopted as a guiding concept for LCA methodology and its application.
- It is important to tackle and include those impacts or stressors which resist measurement. As such, the concept of Resource Availability Infringement has proven useful by providing a placeholder for any impact that can be defined.
- A strategic improvement process can and should be employed as a best practice within LCA, and this principle has been demonstrated through its inclusion within Life Cycle Assessment Towards Sustainability (LCATS).
- Transport, energy and other infrastructure represent core challenges for all businesses in the pursuit of sustainability but remain largely outwith company control. The proactive company will take steps to influence such infrastructure and the life cycle by bring it within operational control, for example by purchasing renewably generated power. Such steps will ensure the long term viability of its operation, and are encouraged through the LCATS approach.
- There is a period of time between now and a sustainable future where problematic situations will arise, such as the need to use unsustainable processes to build sustainable ones. Using coal-based electricity to forge wind turbines is such an example. Acknowledgement of this conundrum during this transitional period is a vital component of the improvement strategy.
- It is recommended that economics are kept out of the LCA process, at least until *unconstrained* improvement options can be generated. In doing so, it is possible to seek economic means to support the improvement options, rather than preclude their possible implementation on the basis of external, unsustainable, monetary pressures.

10.4 Further Research

A general tightening of the RAIL approach is desirable. The decision to have a master RAIL diagram, including all impacts key to the production route was the approach taken here (with ancillary processes on supporting diagrams). To avoid confusion, it may be better to simply have 3 diagrams - one each boundary - or a primary diagram for the operational boundary with supporting RAIL diagrams for the remainder. A comparison of these approaches from the perspectives of clarity and purpose would be valuable. A method for improving the clarity of the link between diagrams within a given lifecycle would be beneficial.

Another area that would definitely benefit from further research and development is the possibility of 'off the shelf' RAIL profiles for common support processes and utilities. This would have the advantage of taking LCATS nearer a tool that could be used *without* expert input in terms of understanding impacts and risk assessment/prioritisation of their remedy. Some further work in this area is already undergoing development at Heriot-Watt University. Testing of the LCATS approach within a wide range of applications would also be beneficial and might reveal further useful modification to the analysis which can be made. It would be useful to further explore and refine the range of strategies for improvement presented in this thesis – especially whether they can be distilled without loss of their comprehensive nature.

Finally, a better understanding of impact to welfare – within the LCA context – is critical to sustainability and the lifecycle field as a whole. A good starting point would be a list of common welfare RAIs such as malnutrition, dehydration, population dislocation, emotional stress etc.

10.5 Final Thoughts

While LCATS puts sustainability at the top of the agenda and might appeal to a new audience, it is important to remember that any LCA is merely an assessment and little more than that. Unless action is taken on its results, no progress will be made at all. LCA practitioners should take up the challenge of sustainability and accept that this includes social effects, such as ensuring the welfare of stakeholders in the life-cycle: they should also recognise that consumption *as well as* destruction of natural capital and resources in general is at the heart of the problem. This reality must be incorporated into all manner of environmental management tools, not just LCA methodology and practice which is the subject of this thesis.

Appendix A - Life Supporting Resources

The purpose of this appendix is to provide an introduction to the resources that support life on earth (i.e. life itself, not just humans). This cannot be an exhaustive list: some resources and services are intangible, and the interrelationships between some resources unknown.

A1 Land and Soil

A1.1 Soil

Soil is the cradle and grave for most terrestrial life. It is a varied mixture of organic matter, living organisms, rock particles, nutrients, gases and water and provides the medium in which countless species of plant take root. Soil is thereby key to the sustenance of not only the plants themselves but also the terrestrial food chain. Humans are also dependent on plants as a source of external energy and a source of raw materials for such uses as clothing, paper, medicine and construction. Maintenance of soil conditions is thus critical for continued life support.

Soil type can dictate the range of plants that might survive and/or thrive in a given location and this in turn effects the insects and animals that might survive and/or thrive in that environment. Changes in soil condition can therefore have profound effects on ecology or, in extreme cases, the ability to support life at all. Such an extreme case can for example be reached through excessive irrigation if salination increases pH to a level that makes the soil sterile as a medium for production.

A1.2 Land and Landscape

Maintenance of natural diversity and function in landscape can be important in the maintenance of site conditions for reasons including shelter for vegetation from prevailing winds, water catchment & drainage (inherent in maintenance of water conditions) and connectivity between the different ecological elements. Regardless of whether any one of these conditions is considered 'good' or 'poor' in agricultural terms, there may be a vital ecology based on these conditions. For example, while farmers have removed many or all hedgerows in farmed arable areas, recent research has shown that this creates additional dependency on pest control due to decline in the bird population, predatory insects and other natural control mechanisms. Hedgerows are also important elements connecting woodland habitats into a network.

Maintenance of site conditions requires direct preservation of:

- organisms including bacteria, fungi, earthworms and insects;
- organic matter, nutrient and water content;
- a suitable pH;
- soil texture/porosity;
- the plants/trees that bind and protect the soil;
- the impact of other elements of the landscape on site ecology.

These requirements are highly inter-dependent and feedback loops are an inherent part of stable ecological systems. By way of example, removal of vegetation can have significant effects on the soil. Some 94% of mudslides that occur annually in the US Pacific Northwest – causing billions of dollars in damage – are thought to have been caused by logging activities [513]. This is an example of a failure to recognise the close interaction of the trees, soil and the hydrological cycle that previously provided stable ecosystems in the region.

A2 Hydrosphere

Water is a key transport mechanism in nature. Water is the medium through which plants gain nutrients from the soil and by which animals transfer warmth and energy around their bodies and cleanse/excrete wastes. It is literally the lifeblood of nature, occurring in nearly all plant, animal and environmental processes [514]. There are two types of water conditions that must be maintained: water quality and water availability.

A2.1 Water Quality

Just as it is a good carrier of nutrients, food and energy, water can also be a distributor of pollutants. It is vital for global life support that natural water resources are not loaded beyond their assimilative capacity with wastes or overwhelmed with chemicals such as fertilisers. Pollutants dissolved in, or carried by water, can result in problems far removed from the source. For example, poisoning of shellfish in the North Sea (off the coast of Germany and Denmark) by nutrient enrichment is thought to be caused by agricultural fertilisers washed down to the sea. The pesticide DDT – now banned in industrialised countries [515] – can bio-accumulate to high concentrations in food chains. It can affect an organism's ability to reproduce and increases vulnerability to disease, parasites and predators.

A2.2 Water Availability

There are times and places where water availability is a more critical issue than water quality. When extraction of ground waters exceeds recharge, the amount of available water is obviously reduced. Other impacts of a lowering of the water table can include subsidence and salination (for example when aquifer water is depleted in coastal areas). Lowering of a water table may have ecological implications as well as the reduced availability of drinking, irrigation or industrial water supplies.

An excess of water quantity may lead to flooding and can also be caused by unsustainable practices. Such practices can result in very serious impacts on water quality such as the availability of drinking water. China's 1998 flood disaster – which killed 3,000 people and left millions homeless – is thought to have been caused by massive illegal logging. Weather was only superficial influence in the disaster as the real blame was recognised as the damage to riverbanks. Logging had removed the ability of the land to absorb and retain water and to hold the soil together.

These requirements make demands of other features of sustainability. For example, vegetative biomass – particularly in the form of trees – regulates water flows, mitigating the effects of excessive precipitation peaks and droughts. The clearance of woodlands from the floodplains of England is believed to have been partly responsible for the rapid rise and fall of the river systems due to the loss of natural forest soils and leaf litter.

Maintenance of water conditions requires preservation of:

- Water availability in the appropriate quantity, quality and season
- The ecological infrastructure of the landscape.
- pH;
- temperature

- nutrient content
- oxygen content
- clarity, and suspended solids within limits.

A3 Atmosphere

The atmosphere is vital to life on earth. Consisting chiefly of nitrogen and oxygen with carbon dioxide and traces of other gases, the atmosphere provides the medium for an invisible link in the hydrological and nutrient cycles. Conditions of the atmosphere, including temperature, pressure, humidity and wind direction together with radiation conditions, comprise what we refer to as the 'weather' (the pattern of weather over a long-term period being referred to as the climate). The atmosphere also provides us with protection from cosmic rays and space debris.

Much of the human intervention in the earth's atmosphere has been through gaseous emissions and airborne wastes. Acid rain and photochemical smog are both examples of pollution episodes relating to gaseous and particulate emissions (usually from combustion of fossil fuels) [516]. CFC refrigerants released into the atmosphere (causing ozone depletion of the earth's stratosphere) is an alarming example of failure to maintain safe and sustainable atmospheric conditions. Stratospheric ozone – depleted in chain reactions with CFCs - blocks harmful ultraviolet radiation that can cause skin cancer/damage to the immune system of humans and other detrimental effects to plants and animals.

Given the chaotic nature of the earth's atmosphere and the global nature of weather systems, it is not possible to define the specific conditions to be maintained (such as water). This does not, of course, rule out our activities having a detrimental effect on atmospheric conditions: maintenance of air quality certainly does require the reduction (if possible cessation) of the very damaging emissions of known pollutants, such as CFCs, SO_x, and NO_x.

The Precautionary Principle must be applied to other emissions. It would, for example, be prudent to avoid interference with the atmosphere since the effects can often be transboundary and intimately tied to other resources, such as soil condition for example.

While the long term effects of the Chernobyl nuclear accident are still relatively local to Chernobyl, the immediate effects were felt across Europe with damaging effects to soils, water and food chains, e.g. through Strontium-90 becoming an ingredient of livestock meat and milk.

A4 Nutrient Cycles

Nutrient cycles are the paths by which the elements which support life on earth are continuously cycled from the abiotic environment (i.e. land, air, water) to living organisms and back to the abiotic environment [517]. These processes are driven by solar energy and gravity. Key nutrient cycles include the hydrological, carbon, oxygen, nitrogen and phosphorous cycles (see Miller [518] for an introduction to nutrient cycles).

Human intervention in these cycles can have serious detrimental effects. For example:

- Both nitrogen and phosphorus in slurry caused by intensive livestock rearing are potential pollutants and can cause eutrophication in water bodies where such effluent is discharged without tertiary water treatment[†††]. Failure to return these nutrients to the land through muck spreading increases the need for agrochemical fertilisers and thus exacerbates other problems associated with fertiliser manufacture (see below). The same is true of human sewage containing nutrients appropriated by the consumption of agricultural produce.

- Harvesting nitrogen rich crops (without rotation with leguminous crops) disrupts the nitrogen cycle by depleting the nitrogen levels of the soil faster than it is replaced through rainfall. Nitrogen is normally replaced using man-made nitrogen fertilisers made using non-renewable fossil resources. Misuse of fertilisers can cause eutrophication[‡‡‡] through agricultural run-off.

††† Tertiary water treatment typically involves the removal of dissolved nutrients following the filtering and removal of organic matter in primary/secondary water treatment.

‡‡‡ Nutrient enrichment of water bodies that can lead to enhanced organic growth causing undesirable effects including algal blooms (see Gilpin, *op. cit.*, p83-85). Algal blooms reduce oxygen content and light penetration.

- The release of oxides of Nitrogen and Sulphur locked up in fossil resources (through combustion) is known to be responsible for acid rain and photochemical smog production [519].

Note that the first two examples actually represent the two ends of a linear nutrient flow that has replaced the natural/traditional flow of nutrients. Whereas human and animal excretions were once returned to the land, forming a loop, there is now a net throughput of nutrients (see Figure 65). Such linear flows have problems associated with both their sources and sinks as described in the above examples.

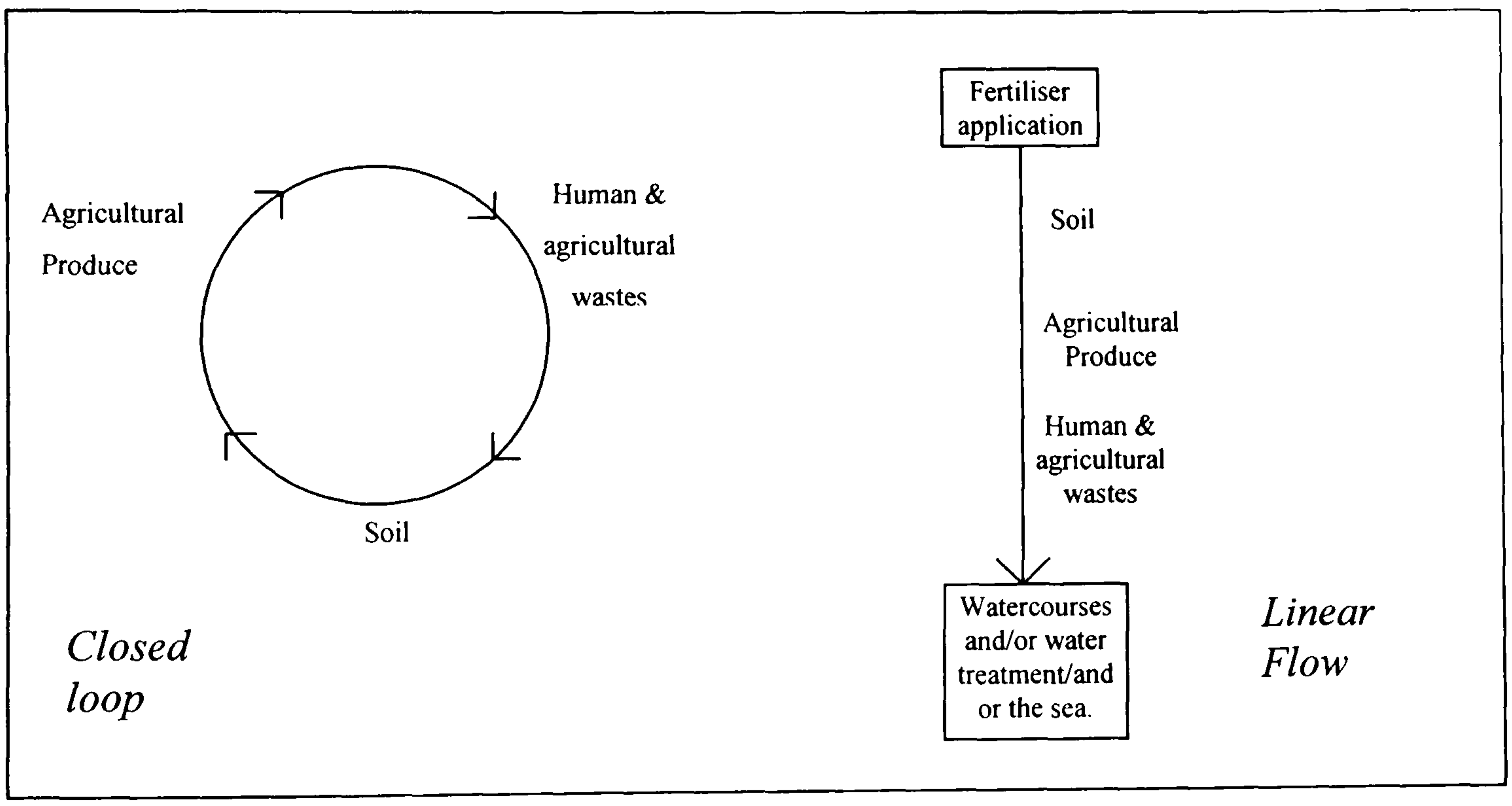


Figure 65 - Closed Loop and Linear Flow Nutrient Pathways

Maintenance of nutrient cycles is necessary to the natural processes that ultimately support the human population. The only way to maintain these cycles is to use nutrients in ways more in tune with nature's processes. This requires breaking the linear patterns of consumption of, for example, underground water reserves. In order to break the linear pattern in the nitrogen example above would require a return to composting and muck-spreading and probably to crop rotation.

A5 Renewable Resources

Renewable resources can be differentiated into biotic (living) and abiotic (non-living) resources. Miller refers to renewables as 'potentially renewable' in order to [520]:

> "emphasise that these resources can be depleted if we use them faster than natural processes renew them".

A5.1 Biotic Renewables

While it might be tempting to assume that renewable *means* sustainable for biotic resources they can, and often are, depleted faster that they can regenerate. Pearce and Turner [521] discuss consumption of renewable resources and the 'critical minimum level of the population' – the minimum level of stock of a population required to prevent extinction. When the rate of consumption exceeds the regeneration rate, it is easy for over-consumption of a renewable resource to approach this minimum level. European governments have now accepted scientific advice that this has occurred in the case of Atlantic Cod stocks requiring drastic curtailment of fishing quotas to protect the longer term future of the Cod and the industry.

It is also important to note that not all biotic resources are renewable in a time frame relevant to humans (see non-renewable resources below). Thus there is still a need for conservation: renewable biotic resources should not be harvested any quicker than they can be sustainably regenerated. That rate should take account of any knock on effects of harvesting to the surrounding ecosystem.

Maintenance of biotic renewable resources requires increased selectivity and efficiency in harvesting. Consumption must not exceed regeneration or cause undue stress on other populations in the ecosystems involved. This necessarily requires risk assessment to be incorporated in – or at least employed in parallel to – life cycle assessment.

A5.2 Abiotic Renewables

Abiotic renewable resources include physical resources such as air & water and sources of energy including solar and wind energy. Water is often a critical renewable resource, particularly where water is drawn from an aquifer (see A2.2). While it is imperative that air and water resources are not abused, renewable energy sources other than biomass and some sources of wind and hydropower (which derive directly or indirectly from solar energy and/or gravity) may be considered potentially infinite. What is important is that the transition to renewable energy is made before fossil resources are depleted and that these energy sources are harnessed in a way that minimises detriment to the natural environment.

Maintenance of renewable abiotic resources requires that physical abiotic resources, such as water, are not removed faster than replenished; and that exploitation of energy sources causes minimal damage to their supporting environments.

A6 Non-renewable Resources

Non-renewable resources can be differentiated into biotic and abiotic non-renewable resources (sections A6.1 and A6.2 respectively). Regardless of abundance, any use of a finite and therefore non-renewable resource is, ultimately, unsustainable. Use of more abundant materials might be deemed *more sustainable* than use of a scarce resource, but the crucial factor is the rate of depletion. Linear consumption of non-renewable resources – typical of modern societies – will ensure exhaustion in the shortest time possible. Problems of depletion of non-renewable resources can be managed if renewable substitutes can be found and exploited at the same rate **and** that substitute renewables are themselves harvested sustainably (again there is a need for risk assessment in determining substitute resources). It is unavoidable that some non-renewables will not have a renewable alternative.

A6.1 Biotic Non-renewables

Areas of ancient woodland and other 'virgin' ecologies exploited as sources of resources (or cleared for other land usage) are considered a non-renewable resource. It can take hundreds of years for tropical hardwoods to grow to maturity, so unless timber is very sparingly harvested from a rain forest for example, not only are the stocks of the trees threatened themselves, but the whole soil and the ecology can be destroyed (by loss of shelter, habitat etc.).

Similarly, peat is a non-renewable resource. Consisting of partly decayed vegetable matter formed over hundreds of years (much more rapidly than fossil resources), peat cannot form at the same rate as it is removed and may not regenerate at all if the hydrology or peat forming flora is irreversibly damaged. In the Rocky Mountains of North America – where peat is extracted for use as soil/ soil conditioner – it is thought that extraction of an 8-11 inch layer removes some 1,000 years of peat accumulation [522].

Maintenance of biotic non-renewable resources requires minimal human intervention of natural ecosystems.

A6.2 Abiotic Non-renewables

Abiotic non-renewable resources include materials such as metal ores, minerals and aggregates. The most widely cited example of depletion of non-renewable resources is our use of the fossil resources coal, gas and oil. Abundance is not so much the issue as there are huge deposits of coal, gas and oil; the problem is the colossal rate with which we consume these resources and their increasingly inaccessible geographical location. In the UK, just 3% of electricity comes from renewable sources [523], while some 70% of UK electricity requirements are met with combustion of fossil fuels [524]. Debate exists over when national or global stocks of coal, gas and oil will be exhausted. These predictions are precariously balanced on the rates of consumption: the smallest change in these rates can render such estimates seriously inaccurate (either way). Other factors include the discovery of new reserves and the technical and economic feasibility of extraction. But since fossil resources are becoming increasingly finite in nature, it is literally only a matter of time before they run out – regardless of however many new reserves are found. Furthermore, their exploitation and use is known to cause damage to other life supporting resources.

Maintenance of non-renewable biotic resources requires increased efficiency in resources use, and that stocks are not depleted any faster than renewable alternatives can be found and (sustainably) exploited.

A7 Conservation of Biodiversity

Biodiversity is of paramount importance to the survival of humans and other living organisms. Biological diversity or 'biodiversity' is described in *The Dictionary of Environment and Sustainable Development* as [525]:

> "an umbrella term to describe collectively the variety and variability of nature. It encompasses three basic levels of organisation in living systems: the genetic, species, and ecosystem levels."

- Genetic diversity within species is important to a species ability to adapt to environmental changes (including those induced by man).
- Species or organismal diversity attracts more popular awareness. At the lower level it is the difference in species within a 'group', e.g. monkeys and elephants are different species within the mammal group. At the higher level there are the differences between the groups, i.e. separating reptiles, mammals, plants etc. UNEP estimate that humans share the planet with between 7 and 20 million other living species – and suggest a working estimate of 13-14 million – yet scientists have only described some 1.75 million species [526].
- Ecosystem or 'ecological' diversity describes the differences to be found between whole ecosystems or habitats.

When biodiversity (as a species or ecosystem) is lost, it is irreversible – in this sense it is a non-renewable resource. Biomass has the potential to be sustainably harvested, but if biodiversity (the differences within and between species, groups and ecosystems) is lost, then the very fabric that supports life on earth is being destroyed. Its thought that as much as 50% of the world's species inhabit rapidly disappearing tropical forests; yet some tropical plants are sources of prescription drugs and the origin of many domestic crops that now form 90% of the world's food [527].

Biotic resources are used directly to provide vital materials such as food, clothing, shelter. Indirect use of biodiversity comes from the ability of biotic systems to maintain themselves (and therefore provide biomass), for example in the maintenance of carbon and oxygen cycles. Biodiversity and the natural environment are intrinsic to our spiritual welfare through aesthetic, cultural and religious values.

A8 Assimilative Capacity

Assimilative capacity is the maximum amount of waste that can be naturally assimilated by a receiving environment without symptoms of pollution or detriment. Natural assimilation is the action of the environment in breaking down – or rendering harmless – a given material. An example of assimilation is of a river breaking down food processing effluent. If however, other sources of biological oxygen demand (BOD) enters the river, the water may become stressed or overloaded and exhibit pollution symptoms such as fish kills and loss of other aquatic life.

Linear consumption of both renewable and non-renewable resources encourages pollution through the non-assimilation of wastes by the environment. Classic examples include the problems of eutrophication, acid rain, ozone depletion, and polluted surface & ground waters. Solid wastes are rarely appropriated by the receiving environment – landfill, for example, does not constitute assimilation and incineration merely puts wastes into a different medium from which most materials originally came, albeit with the recovery of energy.

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